THÈSE

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Tabletop tangible maps and diagrams for visually impaired users

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J'estime qu'entre 1936 et 1937 je mangeai sans payer au comptoir de Capoulade entre mille et mille cinq cents croissants. J'interprétais cela comme une sorte de bourse d'études que l'établissement me consentait.

J'ai conservé une très grande tendresse pour les croissants. Je trouve que leur forme, leur croustillance, leur bonne chaleur, ont quelque chose de sympatique et d'amical. Je ne les digère plus aussi bien qu'autrefois et nos rapports sont devenus plus ou moins platoniques. Mais j'aime les savoir là, dans leur corbeille, sur le comptoir. Ils ont fait plus pour la jeunesse estudiantine que la troisième République.

Romain Gary - La promesse de l'aube.

Ma thèse est terminée, relue, corrigée, relue, corrigée. Dans deux mois aura lieu la soutenance. Une nouvelle fois, ma vie commence et tout reste à faire.

Samuel Page - L'apiculture selon Samuel Beckett.

A la famille Ducasse, et à Michael C.Fry.

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During the last three years, I have not been particularly sociable and I may have not been a very good friend and yet none of my friends resented me for that. I am extremely grateful for their comprehension and above all, the good times I spent with them. I especially want to thank my very dear friends from Bordeaux - Adrien, Anne, Elina and Tibo. I have enjoyed every moment spent with you, whether in Bordeaux, Toulouse or Amsterdam, and they have proved essential to letting off steam. I also want to thank Alice and Mélou for the all too rare but very good moments that we spent together, and I hope we will have more opportunity to see each other once I will no longer be a student. Last but not least, I want to thank some people I met during my studies, namely Colas, Guillaume, Hélène, Kevin and Sophien: it has always been a pleasure to see you and your support and encouragement have always been very much welcomed. I owe each of you a pint of beer, or gin and tonic.

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RÉSUMÉ

(Un résumé plus détaillé de la thèse est présenté à la fin de ce manuscrit, Appendix F.)

En dépit de leur omniprésence et de leur rôle essentiel dans nos vies professionnelles et personnelles, les représentations graphiques, qu'elles soient numériques ou sur papier, ne sont pas accessibles aux personnes déficientes visuelles car elles ne fournissent pas d'informations tactiles. Par ailleurs, les inégalités d'accès à ces représentations ne cessent de s'accroître ; grâce au développement de représentations graphiques dynamiques et disponibles en ligne, les personnes voyantes peuvent non seulement accéder à de grandes quantités de données, mais aussi interagir avec ces données par le biais de fonctionnalités avancées (changement d'échelle, sélection des données à afficher, etc.). En revanche, pour les personnes déficientes visuelles, les techniques actuellement utilisées pour rendre accessibles les cartes et les diagrammes nécessitent l'intervention de spécialistes et ne permettent pas la création de représentations interactives.

Cependant, les récentes avancées dans le domaine de l'adaptation automatique de contenus laissent entrevoir, dans les prochaines années, une augmentation de la quantité de contenus adaptés. Cette augmentation doit aller de pair avec le développement de dispositifs utilisables et abordables en mesure de supporter l'affichage de représentations interactives et rapidement modifiables, tout en étant accessibles aux personnes déficientes visuelles. Certains prototypes de recherche s'appuient sur une représentation numérique seulement : ils peuvent être instantanément modifiés mais ne fournissent que très peu de retour tactile, ce qui rend leur exploration complexe d'un point de vue cognitif et impose de fortes contraintes sur le contenu. D'autres prototypes s'appuient sur une représentation numérique et physique : bien qu'ils puissent être explorés tactilement, ce qui est un réel avantage, ils nécessitent un support tactile qui empêche toute modification rapide. Quant aux dispositifs similaires à des tablettes Braille, mais avec des milliers de picots, leur coût est prohibitif.

L'objectif de cette thèse est de pallier les limitations de ces approches en étudiant comment développer des cartes et diagrammes interactifs physiques, modifiables et abordables. Pour cela, nous nous appuyons sur un type d'interface qui a rarement été étudié pour des utilisateurs déficients visuels : les interfaces tangibles, et plus particulièrement les interfaces tangibles sur table. Dans ces interfaces, des objets physiques représentent des informations numériques et peuvent être manipulés par l'utilisateur pour interagir avec le système, ou par le système lui-même pour refléter un changement du modèle numérique – on parle alors d'interfaces tangibles sur tables animées, ou *actuated*. Grâce à la conception, au développement et à l'évaluation de trois interfaces tangibles sur table (les Tangible Reels, la Tangible Box et BotMap), nous proposons un ensemble de solutions techniques répondant aux spécificités des interfaces tangibles pour des personnes déficientes visuelles, ainsi que de nouvelles techniques d'interaction non-visuelles, notamment pour la reconstruction d'une carte ou d'un diagramme et l'exploration de cartes de type « Pan & Zoom ». D'un point de vue théorique, nous proposons aussi une nouvelle classification pour les dispositifs interactifs accessibles.

ABSTRACT

Despite their omnipresence and essential role in our everyday lives, online and printed graphical representations are inaccessible to visually impaired people because they cannot be explored using the sense of touch. The gap between sighted and visually impaired people's access to graphical representations is constantly growing due to the increasing development and availability of online and dynamic representations that not only give sighted people the opportunity to access large amounts of data, but also to interact with them using advanced functionalities such as panning, zooming and filtering. In contrast, the techniques currently used to make maps and diagrams accessible to visually impaired people require the intervention of tactile graphics specialists and result in non-interactive tactile representations.

However, based on recent advances in the automatic production of content, we can expect in the coming years a growth in the availability of adapted content, which must go hand-in-hand with the development of affordable and usable devices. In particular, these devices should make full use of visually impaired users' perceptual capacities and support the display of interactive and updatable representations. A number of research prototypes have already been developed. Some rely on digital representation only, and although they have the great advantage of being instantly updatable, they provide very limited tactile feedback, which makes their exploration cognitively demanding and imposes heavy restrictions on content. On the other hand, most prototypes that rely on digital and physical representations allow for a two-handed exploration that is both natural and efficient at retrieving and encoding spatial information, but they are physically limited by the use of a tactile overlay, making them impossible to update. Other alternatives are either extremely expensive (e.g. braille tablets) or offer a slow and limited way to update the representation (e.g. maps that are 3D-printed based on users' inputs).

In this thesis, we propose to bridge the gap between these two approaches by investigating how to develop physical interactive maps and diagrams that support two-handed exploration, while at the same time being updatable and affordable. To do so, we build on previous research on Tangible User Interfaces (TUI) and particularly on (actuated) tabletop TUIs, two fields of research that have surprisingly received very little interest concerning visually impaired users. Based on the design, implementation and evaluation of three tabletop TUIs (the Tangible Reels, the Tangible Box and BotMap), we propose innovative non-visual interaction techniques and technical solutions that will hopefully serve as a basis for the design of future TUIs for visually impaired users, and encourage their development and use. We investigate how tangible maps and diagrams can support various tasks, ranging from the (re)construction of diagrams to the exploration of maps by panning and zooming. From a theoretical perspective we contribute to the research on accessible graphical representations by highlighting how research on maps can feed research on diagrams and vice-versa. We also propose a classification and comparison of existing prototypes to deliver a structured overview of current research.

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GLOSSARY

(Definitions given for terms marked with an asterisk are specific to this thesis; definitions given for other terms are commonly found in the literature. In a definition, terms in italics refer to another term defined in the glossary.)

Actuated tangible user interface: *tangible user interfaces* "in which physical components move in a way that can be detected by the user" [242].

Affordance: the design aspect of an object which suggests how the object should be used (see [216]).

Auditory icons: "caricatures of naturally occurring sounds" [75], e.g. a bird sound.

Awareness: in a collaborative context, the understanding of who is changing which parts of the system.

Bi-graphism*: term used by specialized teachers; refers to the concept of designing accessible *graphical representations* that are not solely intended to be tactile, but also visual. Bi-graphic representations rely on tactile elements *and* visual elements (and notably strong contrasts between colors); they are intended to be used by low-vision users or collaboratively between visually impaired and sighted users.

Complexity*: refers to the amount of data that a *graphical representation* conveys. The complexity of a graphical representation depends on the number of elements being displayed and/or on the possibility for the user to interact with them through panning and zooming.

Constructive assemblies: *tangible user interfaces* "that involve the interconnection of modular physical, interactive units to formulate larger constructions that are automatically or manually put-together" [162].

Container: one of three types of *tangible object* defined by Holmquist et al. [102]: "containers are generic objects used to move information between different devices or platforms". See *token* and *tool*.

Data physicalization: see Physicalization.

Diagram*: a *graphical representation* that is not a table, an icon, a sign, an image or a map. Broadly speaking, diagrams are "illustrations that express conceptual relationships spatially" [343].

Digital*: quality of a representation that cannot be explored tactilely (i.e. using both hands), that is virtual.

Digital maps and diagrams*: *interactive maps and diagrams* that do not rely on a *physical* representation and that most commonly provide one (or two) *points of contact*.

Dynamic*: quality of a representation or display that can be instantly updated. We consider that there is a continuum between representations that cannot be updated at all (s*tatic)* and graphical representations that can be fully and instantly updated by a system (*dynamic*).

Earcon: “abstract, synthetic and mostly musical tones or sound patterns that can be used in structured combinations” [47].

Editable*: quality of a *graphical representation* that is *digital* and that can be directly modified by the user.

Expressiveness*: refers to the nature of the data that a *graphical representation* conveys and notably to the different *implantations* and marks used: points (squares, triangles, arrows, etc.), lines (dotted, plain, of various thicknesses), areas (filled, half-filled, etc.). The larger the range of marks used, the more expressive the graphical representation.

Fiducial marker: in the context of this thesis, tags that are attached *to tangible objects* that allow the application to track the objects and to retrieve their position (x-, y- and possibly z- coordinates), as well as their orientation. Fiducial markers are often printed on a piece of paper but can also be directly embedded/engraved in the *tangible objects*.

German film / paper: a transparent plastic sheet that must be placed on a rubber mat before being drawn on using a stylus or a pen. When drawing, a raised image is created that visually impaired users can immediately detect (see Figure 2.4, right).

Graphical primitives: see *implantation*.

Graphical representation: a document (*digital* or *physical*) that is composed of a set of marks [243] and that is not solely based on textual information. Includes maps, diagrams, icons, signs, images and tables. In the context of this thesis, we used the expressions “graphical representations”, “representations” and “maps and diagrams” interchangeably, to avoid repetition.

Hybrid maps and diagrams*: *interactive maps or diagrams* that rely on a *digital* and *physical* representations and therefore provide multiple *points of contact* and support multiple hand/finger exploration.

Implantations: *graphical representations* are composed of marks, which can be categorized into three types of *implantation* [15]: points, lines and areas. These *implantations* constitute the elementary units or *graphical primitives* of any graphical representation.

Interactive maps and diagrams*: any type of prototype that allows visually impaired users to access *maps* or *diagrams* in an interactive manner.

Manipulable*: quality of a representation that is composed of several (tangible) objects that the user can physically grasp and move. The easier it is to move the objects, the more “manipulable” the representation is.

Maps: “geographic representations that facilitate a spatial understanding of things, concepts, conditions, processes or events in the human world” [344].

Orientation & Mobility: a profession which focuses on educating individuals who are blind or visually impaired on safe and effective travel in their environment.

Orientation & Mobility maps: *maps* intended to be used to help a person navigate.

Point of contact: an element of the representation that is currently being explored, either indirectly, by means of a pointing device, or directly, by the user’s hands or fingertips. See *digital* vs *hybrid* maps and diagrams.

Physical*: quality of a representation that provides *multiple points of contact*; that can be explored tactilely (i.e. with both hands). Antonym: *digital*.

Physicalization: the term refers to both “a physical artifact whose geometry or material properties encode data” [121], and emergent research that “examines how computer-supported, physical representations of data (i.e., physicalizations), can support cognition, communication, learning, problem solving and decision making” [121].

Raised-line graphic: a *graphical representation* printed on a special heat-sensitive paper (called swell or microcapsule paper) containing microcapsules of polystyrene, using a normal printer. When the sheet passes through a heater, printed areas in black are heated at a higher temperature than non-printed areas, causing the microcapsules under the ink to swell. This creates a relief that the user is able to detect.

Raised-pin displays: devices composed of a matrix of pins that can be dynamically raised or lowered and that are used to display graphical information. Raised-pin displays could be referred to as “Braille tablets”.

Reconfigurable*: quality of a representation that is composed of several tangible objects that can be physically moved by the system (see *dynamic*) and/or the user (see *manipulable*). In addition, a key property of *TUIs*.

Refreshable*: synonym of *dynamic*.

Scalability: ability for a system to adapt to complex problems or data sets [276].

Spearcons: “spoken phrases sped up until they may no longer be recognized as speech” [47].

Static*: quality of a representation that cannot be updated. Antonym: *dynamic*.

Swarm User Interfaces: “human-computer interfaces made of independent self-propelled elements that move collectively and react to user input » [81].

Tactile graphics: *graphical representations* intended to be read principally by touch rather than vision [1].

Tangible object*: any object that is used in a *tangible user interface*.

Tangible user interaction: “a genre of human-computer interaction that uses spatially reconfigurable physical objects as *representations* and *controls* for digital information” [306].

Tangible User Interfaces (TUIs): interfaces that use spatially reconfigurable physical objects as *representations* and *controls* for digital information.

Token: one of three types of tangible object defined by Holmquist et al. [102]: “tokens are used to access stored information, the nature of which is physically reflected in the token in some way”. See *container* and *tool*.

Token+constraint interfaces: a sub-type of TUIs that rely on “two kinds of physical/digital artifacts: *tokens* are discrete, spatially reconfigurable physical artifacts that each describe or represent an element or aggregate of digital information. *Constraints* are structures that physically channel how tokens can be manipulated, often limiting their movement to a single physical dimension” [306].

Tools: one of three types of *tangible object* defined by Holmquist et al. [102]: “*tools* are used to manipulate digital information”. See *container* and *token*.

Updatable*: quality of a representation (*digital* or *physical*) that can be modified, either by the system or by the user.

Versatility: quality of an interface that can embrace a variety of subjects or fields.

CHAPTER 1

INTRODUCTION

> *Ça a duré ce que ça a duré, mais l'Institut des Aveugles me fut d'un grand secours. Tous les soirs, après le travail, je m'y rendais, et je me postais à l'entrée. Vers sept heures, les aveugles commencent à sortir. Avec un peu de chance, je réussissais à m'emparer de six ou sept et à les aider à traverser la rue. On m'objectera qu'aider un aveugle à traverser la rue, ce n'est pas grand-chose, mais c'est toujours ça de pris. En général, les aveugles sont très gentils et très aimables, à cause de tout ce qu'ils n'ont pas vu dans la vie. […] Et puis un jour je suis tombé sur un aveugle qui n'était pas diminué du tout. […]. Je ne sais pas comment il a su que c'était moi, mais il m'a reconnu tout de suite. – Foutez-moi la paix, gueula-t-il. Allez faire vos besoins ailleurs ! Et puis il a levé sa canne et il a traversé tout seul.*
>
> Romain Gary (Emile Ajar). Gros-Câlin.

Chapter structure

1. Context: visual impairment and blindness
2. Why study tangible maps and diagrams for visually impaired users?
3. Thesis statement
4. Research questions
5. Contributions
6. Thesis structure
7. Remarks

1 CONTEXT: VISUAL IMPAIRMENT AND BLINDNESS

This thesis concerns the development of accessible maps and diagrams for visually impaired people. Before considering the motivations of this work, it is important to define to which part of the population the term "visually impaired people" refers. Two measures are mainly used to distinguish between the various degrees of visual impairment: visual acuity and visual field [337]. Visual acuity measures the clarity or sharpness of vision and is expressed as a ratio of two numbers: the numerator is the distance at which a person can discriminate between two objects; the denominator is the distance at which a person with no visual deficit can discriminate between these two objects. The visual field is expressed in degrees and indicates the area in which an object can be detected in the peripheral vision while the eye is focused on a central point. Based on these measures, the latest International Classification of Diseases (ICD) [338] defines blindness as a visual acuity worse than 3/60 or a visual field of the better eye no greater than 10°. Blindness may include light perception, provided that the visual acuity is less than 3/60. Moderate or severe visual impairment, also referred to as low-vision, is defined by a visual acuity worse than 6/18 (moderate) or worse than 6/60 (severe), but equal to or better than 3/60. In this thesis, we use the term "visual impairment" to refer to moderate and severe visual impairment as well as blindness, as is the case in the ICD. Even though the interaction techniques and prototypes that we proposed were specifically designed for blind people, i.e. they did not rely on visual feedback, we use the term "visually impaired users" to emphasize the fact that our work could benefit people affected by blindness as well as people having low-vision.

Most recent estimates of blindness and visual impairment were provided by the World Health Organization (WHO) [337]. In 2010, the estimated number of visually impaired people was 285 million, including 39 million individuals affected by blindness and 246 million individuals affected by low-vision. In Europe, the estimated numbers were 31.7 million visually impaired people, 28.7 having low-vision and 3 million being blind. These estimates should be considered cautiously, due to missing or outdated data (the margin of error is approximatively 20%). Around the world, the main causes of visual impairment, including blindness, are uncorrected refracted errors (43%), cataracts[1] (33%) and glaucoma[2] (2%).

One of the main consequences of visual impairment, from a societal perspective, is high unemployment rates. For example, in the United States, a 2015 report indicates that only 42% of working-age people with visual impairment are employed, in comparison to 78% for people without any disability [58]. This unemployment rate is also correlated with low income: the same report states that in the United States, 29% of visually impaired people live below the poverty line. Issues related to employment can be explained by the fact that visually impaired people often experience difficulties in navigating independently (due to the inaccessibility of maps and the lack of accessible and reliable navigation systems), but also because they have a limited access to digital or printed information, and especially to graphical information. In fact, Beck-Winchatz and Riccobono [10] commented upon how the inaccessibility of curriculum materials might explain why visually impaired people do not pursue careers in a number of disciplines, and especially in

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[1] A cataract is a cloudiness or opacity in the normally transparent crystalline lens of the eye.

[2] Glaucoma is a group of diseases that damage the eye's optic nerve.
https://nei.nih.gov/health/glaucoma

Science, Technology, Engineering and Mathematics. Regardless of employment considerations, the fact that visually impaired users are not guaranteed an equal access to (digital) information raises social issues, notably in terms of inclusion.

Some assistive technologies have contributed to a greater access to digital information, the most notable being screen-reader technology[3]. A screen-reader is a piece of software that extracts the text being displayed on a screen and outputs it using a speech synthesizer or a braille display. Combined with a keyboard or a set of multitouch gestures, screen-readers allow visually impaired users to interact with a computer or a mobile device and are the most common technology used by visually impaired people to access digital content. However, because they mainly rely on a sequential access to digital information, screen-readers are not adapted to convey graphical representations. In fact, and as we will more thoroughly describe in the next section, to date there is no mainstream assistive technologies with which visually impaired people can independently access graphical representations, which strongly affect their access to education and employment as well as their independence, quality of life and social inclusion.

2 WHY STUDY TANGIBLE MAPS AND DIAGRAMS FOR VISUALLY IMPAIRED USERS?

2.1 IMPORTANCE OF GRAPHICAL REPRESENTATIONS

Graphical representations are part of our societies and cultures. Even during the prehistoric era, map-like representations were produced by "primitive people" using a variety of materials such as shells, stones and sticks to communicate about spatial relationships [286]. For millennia, the diversity of these materials evolved alongside the goals, techniques and users of graphical representations. For long reserved to a small minority of people such as "priests, scholars or bureaucrats", graphical representations, through technological advances, have progressively become more and more commonplace [345]. The invention of the printing press by Gutenberg in the middle of the fifteenth century is, for example, considered as a key technological progress. But certainly one of the most important milestones was the development of the web, which allowed for easy and cheap dissemination of graphical representations to a large audience. In particular, from the mid-nineties, online mapping services such as MapQuest (1996), Open Street Map (2004) and Google Maps (2005) started to emerge, soon becoming mainstream services. In parallel, disciplines such as Information Visualization and Geographic Visualization emerged and participated in the expansion of interactive and most often dynamic digital graphical representations. Nowadays, maps and diagrams–a subset of graphical representations that we define in Chapter 2, Part A–play a crucial role in our lives, be it as educational tools, navigational aids or means of communication for online and printed content.

2.2 VISUALLY IMPAIRED PEOPLE AND ACCESS TO GRAPHICAL REPRESENTATIONS

Despite the fact that their availability is often taken for granted in developed countries, visually impaired people have not benefited from the growing development of interactive graphical

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[3] In France, about 95% of people who are visually impaired use a screen-reader [61].

representations. Due to their lack of tactile feedback, digital or printed graphical representations remain inaccessible to visually impaired people who cannot explore them using the sense of touch. Consequently, while the amount of data, technologies and interaction techniques available to sighted people is continuously increasing, visually impaired people have an extremely limited access to graphical representations and, needless to say, to interactive and dynamic graphical representations. This lack of availability can be partially explained by societal, technological and perceptual considerations – the last two being intrinsically connected.

From a societal perspective, the cognitive abilities of visually impaired people have long been debated and discussed [313]. Three theories have been proposed to discuss whether visually impaired people could understand spatial concepts such as understanding a map or being able to distinguish between various geometric shapes [66]: the "deficiency" theory stipulates that visual experience is essential to develop and understand spatial concepts; the "inefficiency" theory considers that visual experience is not essential but that the lack of visual experience necessarily leads to inefficient or at least less efficient spatial abilities; the "difference" theory states that visual experience is not necessary and that other senses can be used to develop spatial abilities that may be of a different nature but can be as functional as those developed by sighted users. The first theory is now invalidated, as a number of empirical studies demonstrated that visually impaired users are able to understand spatial concepts and that they can acquire spatial knowledge with direct (e.g. while navigating an unknown environment) or indirect (e.g. by reading a tactile map) experience. Although the two other theories have coexisted for several decades the latter is now the most widely considered. In particular, it is now well acknowledged that visually impaired people's spatial abilities may be correlated with (a lack of) familiarity with specific tasks and the development of effective strategies to encode and understand information, rather than to the characteristics of the haptic system per se.

However, the "inefficient" theory and similar positions have been prevalent for a long period of time and up to the fifties research activities more commonly addressed the understanding and benefits of graphical representations (and particularly of maps) for visually impaired users from a cognitive perspective, and little research focused on how to make them more widely available by building upon technological advances. In fact, as observed by Brock [23], the number of research projects concerning the development of interactive map prototypes only began to increase considerably around the year 2000, i.e. at a time at which interactive graphical representations had already started to become mainstream for sighted people. Since then, research on non-visual graphical representations is a long way from having caught up with research and development of visual representations, and the gap between sighted and visually impaired people's access to graphical representations is constantly growing. While there is an increasing development of online, interactive and dynamic representations for sighted people, visually impaired users barely have access to any graphical representation outside of schools. In addition, the graphical representations they have access to, referred to as tactile graphics, suffer from several limitations. They must be produced by tactile graphics specialists using particular techniques that require dedicated material, and time; they are non-interactive; they cannot be updated once printed. As for prototypes of interactive maps and diagrams, they are mostly confined to research laboratories and only a few of them are close to being regularly used within specialized education centers (e.g.

[28]). Therefore, as stated by O'Modhrain et al. [219], "there is an immediate need for research and development of new technologies to provide non-visual access to graphical material".

However, the same authors also pointed out that "while the importance of this access is obvious in many educational, vocational, and social contexts for visually impaired people, the diversity of the user group, range of available technologies, and breadth of tasks to be supported complicate the research and development process" [219]. In fact, the development of (interactive) graphical representations for visually impaired users raises several challenges, mainly because of the inherent properties of tactile perception. As we will more thoroughly discuss in the first chapter of this thesis (Chapter 2, Part B, 5), the tactile exploration of a graphic is more sequential than its visual exploration because the cutaneous system only acquires information when the users' fingertips and/or palms are in contact with the surface of the tactile graphic. In addition, the spatial resolution of touch is limited compared to that of vision, meaning that it is not possible to display the same amount of information on a visual graphic as on a tactile graphic of the same size. From this, two considerations follow. Firstly, visual graphical representations must be adapted to tactile graphical representations, and this adaptation process needs to be performed by tactile graphics specialists. Secondly, displays must take into account the properties of tactile perception and notably the fact that tactile exploration is cognitively demanding as users must integrate several pieces of information over space and time [159]; therefore displays should be carefully designed, so as to reduce cognitive workload.

The question of the adaptation of content is crucial when discussing the availability of graphical representations. The fact that the production of tactile graphics is a time-consuming and costly process partly explains why non-interactive tactile graphics are still inaccessible to visually impaired users outside of schools. However, the development of Open Data initiatives as well as efficient algorithms to process them opens new avenues for the (semi) automatic adaptation of content. It is now possible to envisage that in a few years it will be possible to automatically adapt simple online visual representations. Most complex representations will probably still require manual intervention but the cost and time of production will undoubtedly be drastically reduced.

2.3 INTERACTIVE GRAPHICAL REPRESENTATIONS FOR VISUALLY IMPAIRED USERS

The growth of available content must go hand in hand with the development of affordable and usable devices. In particular, these devices should provide users with an independent access to interactive and updatable graphical representations. The main advantage of interactivity is that it makes the use of braille labels unnecessary, which frees space for additional content (braille labels takes a lot of space) and makes graphical representations accessible to a larger audience (the number of braille readers is continuously decreasing). Updatable graphical representations are necessary to support advanced functionalities such as filtering, highlighting, panning and zooming that will guarantee a functional equivalence between visual and tactile graphical representations, but they also open new possibilities in terms of supported tasks, such as annotating or editing a map or a diagram.

Different approaches have already been considered to develop interactive maps and diagrams for visually impaired users and can be classified into two broad categories. On the one hand, a number of prototypes rely on digital representations that are displayed on a screen or projected over a surface: users can explore them using one finger or an input device such as a keyboard, a stylus, a joystick, etc. Audio feedback (and possibly force or cutaneous feedback) is provided according to what is under the finger or the cursor. These prototypes have the great advantage of being instantly updatable, but they provide very limited tactile feedback, which makes their exploration cognitively demanding and imposes heavy restrictions on content.

On the other hand, a number of prototypes rely on digital and physical representations. The most common approach, which we referred to as interactive tactile displays, is to place a tactile overlay (the physical representation) above a tablet: via the materiality of the tactile graphic, users can explore the representation using both hands; and via the tablet, they can also interact with it using multitouch gestures. These prototypes allow for a two-handed exploration that is both natural and efficient for retrieving and encoding spatial information, but they are physically limited by the use of a tactile overlay, making them impossible to update. Other types of prototypes that rely on digital and physical representations exist, but they are extremely expensive (e.g. braille displays, also referred to as raised-pin displays) or offer a slow and limited way to update the representation (e.g. maps that are 3D-printed based on users' inputs [292]). As for Tangible User Interfaces (TUIs), which we describe in the following section, up to now, they have rarely been investigated for visually impaired users.

2.4 FROM TANGIBLE USER INTERFACES TOWARDS PROGRAMMABLE MATTER

As online graphical representations began to become commonplace, notably as a result of advances in the broad field of Visualization (including Information, Scientific and Geographic Visualization), a group of researchers from the MIT started to investigate how to bridge the gap between the physical and digital worlds. Graspable User Interfaces were first introduced by Fitzmaurice et al. [64] and were composed of several physical handles that the users could manipulate in order to directly interact with digital information. This new type of interface offered several advantages, among which the fact that it "encourages two handed interaction" and "facilitates interactions by making interface elements more 'direct' and more 'manipulable' by using physical artifacts" [64]. In a nutshell, this type of interface allows users to interact with physical and updatable representations. These interfaces were later designated as *Tangible User Interfaces* (TUI) [113] and soon become a fully-fledged research area whose community is still very active. The main idea underlying the design of TUIs is to combine digital representations with tangible (i.e. composed of physical objects) and intangible (i.e. audio and video projections) representations.

TUIs have paved the way for innovative types of interfaces calling for a greater updatability and physicality. Indeed, one limitation of TUIs is that they cannot be as easily updated as purely digital representations because they rely on real physical objects. To address this issue, alternatives have been proposed that rely on the use of tangible objects that can be moved by the system or that can move independently (e.g. small robots). This type of interface, referred to as *actuated tabletop TUIs*, allows for a greater updatability and, although more expensive than traditional tabletop TUIs, remains affordable. The promising development of actuated tabletop TUIs makes it possible to envisage S*warm User Interfaces* (SUIs) composed of a high number of small mobile tangible objects that could act as physical pixels and whose spatial layout could be used to display highly dynamic and yet physical graphical representations.

Another alternative lies in the development of *shape displays*, which do not rely on a set of distinct objects but on a single surface whose geometry can be controlled by a computer, similar to “digital clay”. These last two fields are strongly associated with the emerging field of *data physicalization*, which, although not limited to interactive or dynamic representations, “uses physical data representations to help people explore and communicate data” [121]. Illustrative examples of physicalizations include 3D-printed bar charts or arrays of motorized bars (see InForm [68] for example). All these novel types of interfaces can be considered to be part of a vision of highly updatable and physical interfaces driven by researchers from the MIT Media Lab[4], the pioneer lab of TUIs. This vision, referred to as Radical Atoms, is represented by the idea of Programmable Matter: “*Radical Atoms* is our vision for human interactions with dynamic physical materials that are computationally transformable and reconfigurable. Radical Atoms is based on a hypothetical, extremely malleable, and dynamic physical material that is *bidirectionally* coupled with an underlying digital model (bits) so that dynamic changes of the physical form can be reflected in the digital states in real time, and vice-versa” [112].

2.5 BRIDGING THE GAP BETWEEN NON-VISUAL PHYSICAL AND DIGITAL WORLDS

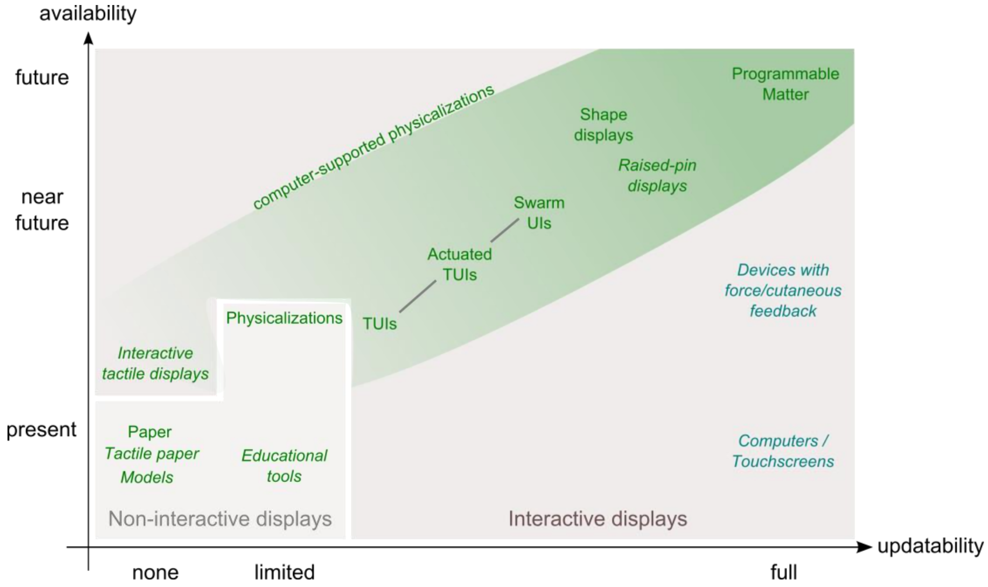

Figure 1.1. Different types of displays that can be used to make graphical representations accessible to sighted or visually impaired users, according to their degree of availability and updatability. Displays for visually impaired users that are commonly used or studied are written in italics. Devices that are not *physical* (i.e. that do not support multiple hand/finger exploration) are written in blue.

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[4] https://www.media.mit.edu/

Figure 1.1 is an attempt to summarize the various types of technologies that have been used to make graphical representations accessible to visually impaired and sighted users, according to their degree of updatability and availability. The figure illustrates that research on physical graphical representations (in green) ranges from non-updatable representations (such as 3D-printed bar charts or printed maps) to fully updatable representations instanced by the idea of Programmable Matter. In between, a number of interfaces have and are being designed, including standard TUIs, actuated tabletop TUIs and shape displays.

The very concept of Programmable Matter is still a pure theoretical concept and has not been implemented yet. As for shape displays, despite the fact that they are being studied more and more, they are still in their infancy and are complex and/or expensive to build. Therefore, in the near future, non-actuated and actuated tabletop TUIs appear to be the most promising technologies to support the display of physical and updatable graphical representations. In fact, a number of TUIs are already used outside of research laboratories, in schools or museums, and the development of recent actuated tabletop TUIs (e.g. [81] and [223]) suggests that such interfaces could become more and more common in a couple of years.

However, research on graphical representations for visually impaired users has mainly focused on physical but non-updatable representations (such as tactile graphics, models or interactive tactile displays) or on updatable but non-physical representations (in blue). Very few prototypes of (actuated) TUIs for visually impaired users have been proposed, despite their advantages in terms of exploration and updatability. Besides, existing TUIs for visually impaired users have not been implemented or formally evaluated, which makes it very unclear to what extent the proposed interaction techniques and technical solutions are feasible and usable. One notable exception is the work of McGookin et al. [196], who implemented and evaluated a tabletop TUI that enables visually impaired users to access bar charts and line graphs, and who were the first to propose guidelines for the design of non-visual TUIs. Their work opened up new avenues for the design of interactive, physical and updatable maps and diagrams for visually impaired users and suggests that research on TUIs should not be restricted to sighted users and could be highly beneficial for visually impaired users as well. Building on this promising work and on research on visual graphical representations, we therefore aim to bridge the gap between the non-visual digital/updatable and physical/static worlds.

3 THESIS STATEMENT

There is a lack of research concerning the development of affordable, interactive, physical and updatable graphical representations for visually impaired users. Physicality is important to support strategies of multiple hand/finger exploration; updatability is important to support advanced functionalities (e.g. panning and zooming) and tasks (e.g. edition and reconstruction). In this thesis, we suggest that **actuated and non-actuated tabletop Tangible User Interfaces could fill this gap, by providing visually impaired users with an independent access to physical and yet updatable maps and diagrams**.

4 RESEARCH QUESTIONS

The central research question of this thesis is to investigate **to what extent tangible interaction can be used to make updatable maps and diagrams accessible to visually impaired users**. As we briefly discussed in the previous sections, TUIs are limited by the use of tangible objects: their size, number and "expressivity" (i.e. what type of information they are able to represent) limit how complex the tangible representation can be. In particular, in the absence of vision, it is not possible to rely on visual feedback to enhance the tangible representation. Other constraints must be taken into account when designing TUIs for visually impaired users, such as providing audio feedback to compensate for the absence of visual feedback, and ensuring that the tangible objects remain stable during exploration. Given these considerations, our thesis was driven by the following research questions:

Research Question 1: What are the benefits and limitations of tangible maps and diagrams compared to current practices and existing research prototypes?

a. What are the current practices and what are their benefits and limitations?
b. Which approaches have been considered by researchers and what are their benefits and limitations?
c. What are the known benefits of TUIs and to what extent these benefits may be relevant to visually impaired users?
d. What are the inherent limitations of TUIs and are there further limitations specific to TUIs for visually impaired users?

Research Question 2: How to design tangible maps and diagrams for visually impaired users?

a. What are the design challenges specific to TUIs for visually impaired users?
b. Have these design challenges been addressed in the literature, and if so, were the proposed solutions satisfying?
c. How to address design challenges for which no suitable solutions have yet been proposed?

Research Question 3: Given the limitations inherent to TUIs and specific to TUIs for visually impaired users, what is the design space of tasks and graphical representations supported by TUIs for visually impaired users?

a. Which tasks can be supported by (or particularly adapted to) tabletop tangible maps and diagrams for visually impaired users?
b. What type of graphical representation can be made accessible with TUIs? How *complex* and *expressive*[5] tangible maps and diagrams can be?

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[5] In this thesis, we consider that the *complexity* of a graphical representation is related to the amount of data that it conveys, while the *expressivity* of a graphical representation is related to the nature of data that it conveys. For example, visual maps can be used to convey information about landmarks, streets, railways, parks, etc. and are often very expressive; their complexity depends on the number of elements being displayed and/or on the possibility for the user to interact with them through panning and zooming. See Glossary.

To answer these questions we developed three tabletop TUIs that support a variety of tasks and graphical representations and that rely on different technical solutions. The question of the usability of these interfaces (i.e. the extent to which they can be used "with effectiveness, efficiency and satisfaction in a specified context of use" [114]) is therefore intrinsically linked to the three previous questions. We addressed the question of usability by conducting user studies through which we assessed, with quantitative and/or qualitative methods, a variety of aspects, such as the design of tangible objects, the potential benefits of TUIs for learning and the effect of "panning and zooming" on mental representations. Therefore, this fourth question must be taken in a broad sense: **Research Question 4: Are the proposed interfaces usable?**

5 CONTRIBUTIONS

To address these questions, we review a number of research areas related to maps and diagrams for visually impaired users (RQ1; Chapter 2, Part B and Chapter 2, Part C) and to TUIs (Chapter 2, Part D). We then discuss how TUIs could be used to design physical and updatable maps and diagrams and, based on the analysis of existing prototypes, identify a number of aspects that should be taken into account when designing TUIs for visually impaired users (RQ1 and RQ2; Chapter 2, Part E). The design of three tabletop TUIs allows us to propose technical solutions and interaction techniques that address a number of design challenges (RQ2, Chapter 3, Chapter 4 and Chapter 5). With these TUIs, we cover various tasks as well as graphical representations of various complexities, therefore allowing us to better determine the design space of tasks and graphical representations (RQ3, Chapter 3, Chapter 4 and Chapter 5).

More precisely, our contributions are as follows:

1) We propose a new classification for interactive maps and diagrams for visually impaired users and analyze the different approaches that have been proposed.
2) We analyze existing prototypes of tangible maps and diagrams and identify a number of design considerations according to four dimensions: content, tangible objects, interactivity, technology.
3) We describe two non-actuated tabletop TUIs, the Tangible Reels and the Tangible Box, which support the (re)construction, manipulation and edition of tangible maps and diagrams by visually impaired users.
    a. We propose new types of stable and easy to manipulate tangible objects.
    b. We describe a set of interaction techniques for the reconstruction and exploration of maps and diagrams and reflect upon additional features (annotation and construction).
    c. We present two user studies and one educational workshop conducted to assess the usability of the Tangible Reels.
    d. We report on participatory design sessions conducted with specialized teachers in the framework of the Tangible Box project.
4) We describe BotMap, an actuated tabletop TUIs for the exploration of tangible maps with panning and zooming.
    a. We describe two interfaces based on discrete (Keyboard Interface) vs continuous (Sliders Interface) panning and zooming.

   b. We present a set of functionalities and navigational aids that help users explore and understand "pan & zoom" maps.
   c. We describe three studies conducted to compare the usability of the two interfaces; to assess whether visually impaired users can understand maps whose exploration require panning and zooming and whether one interface leads to better performances and/or satisfaction; to investigate which navigational aids could help users to better navigate and understand the maps.

5) We discuss different perspectives for (actuated) tabletop TUIs for visually impaired users. In particular, we discuss the potential of TUIs to foster collaboration between sighted and visually impaired users through ongoing projects in which we are involved, and illustrate the feasibility of dynamic geophysicalizations for visually impaired users with a proof-of-concept prototype of an actuated bar chart.

6 THESIS STRUCTURE

This thesis is structured as follows. Chapter 2 gives an overview of several fields of research related to the design of (interactive) maps and diagrams for visually impaired users, and is composed of five parts. In Part A, we define the nature of maps and diagrams and discuss their benefits. In Part B, we present and discuss current practices to make maps and diagrams accessible to visually impaired users as well as important notions relating to tactile perception. In Part C, we propose a new classification for interactive maps and diagrams for visually impaired users, and, based on several examples, discuss the advantages and drawbacks of existing approaches. In Part D, we provide an overview of the field of tabletop TUIs. In Part E, we describe and analyze existing prototypes of tangible maps and diagrams for visually impaired users and highlight a number of design challenges that have not yet been addressed.

Chapter 3 introduces Tangible Reels, a tabletop TUI that enables visually impaired users to independently reconstruct tangible maps and diagrams of varying complexities. This interface was inspired by current practices and relies on an innovative type of tangible objects called Tangible Reels, the design of which we describe in detail. The chapter also presents a set of interaction techniques, two user studies and observations made during one educational workshop.

Chapter 4 describes the design of the Tangible Box, a low-cost and compact tabletop TUI that can be used to augment traditional supports (e.g. static tactile graphics) and supports the construction, manipulation and exploration of tactile and tangible graphical representations by visually impaired students. Although at the time of writing this prototype has not yet been evaluated, we present its design and implementation and report on participatory design sessions conducted with specialized teachers.

Chapter 5 introduces BotMap, an actuated tabletop TUI that enables visually impaired users to explore maps by panning and zooming. In this chapter, we describe two interfaces that rely on different panning and zooming implementations and input devices (the Keyboard and Sliders interfaces), and report on the results of three user studies conducted to assess the usability of the interface, notably in terms of navigation and comprehension performances.

Chapter 6 summarizes our contributions by reframing them within our research questions. In addition, based on our findings, we discuss the scope of this thesis from two perspectives: the users' profiles (blind, low-vision and sighted users) and the nature of the graphical representations (maps and diagrams). We also discuss to what extent the interfaces that we developed are related to other fields of research and lay out perspectives for further research, some of which we illustrate with ongoing projects on which we were or are engaged, either as supervisor or collaborator.

In Chapter 7, we discuss the pros and cons of the interfaces that we developed when compared with existing approaches, reflect upon how "tangible" are these interfaces and conclude by proposing a far-reaching agenda for further research.

7 REMARKS

7.1 THE ACCESSIMAP PROJECT

This thesis is part of the AccessiMap research project funded by the National Research Agency of France. The AccessiMap project aims at improving the accessibility of maps for visually impaired users–hence the fact that even though we decided to consider maps *and* diagrams, this thesis is slightly more focused on maps. The AccessiMap project brings together two research laboratories (IRIT[6], Toulouse, France, and Telecom ParisTech[7], Paris, France), a company that develops open software (Makina Corpus[8], Toulouse, France), and a specialized education center for blind and visually impaired people (CESDV-IJA[9], Toulouse, France).

Broadly speaking, the question of the accessibility of maps is addressed from three different perspectives: 1) the company works in close collaboration with tactile graphics specialists and teachers of the Institut des Jeunes Aveugles (IJA) to develop a software that aims to facilitate the production of interactive tactile graphics [52]; 2) a working interactive tactile map prototype is being used in situ by teachers and students at the IJA: its uses and benefits have been investigated from a design perspective (PhD work of Emeline Brulé, see [28] for example) and several students have worked and are working on the design and evaluation of adapted learning activities; 3) advanced interaction techniques for the exploration of maps are investigated, including smartwatch-based interactions (PhD work of Sandra Bardot, see [6] for example) and tangible interaction (this thesis).

7.2 CONVENTIONS AND CREDITS

We use the pronoun "we" in the entire thesis, as the works that we describe have been conducted with Christophe Jouffrais, Marc Macé and Bernard Oriola, who are respectively supervisor, co-supervisor and "unofficial" supervisor of this thesis. Some works have been done in collaboration with other colleagues or students. In particular, part of the classification described in

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[6] https://www.irit.fr/

[7] https://www.telecom-paristech.fr/eng/research/research-centre-digital-technology.html

[8] https://makina-corpus.com/

[9] Centre d'Education Specialisée pour Déficients Visuels (Specialized education center for the visually impaired) – Institut des Jeunes Aveugles (Young Blinds' Institute).

Chapter 2, Part C has been proposed in collaboration with Anke Brock; the Tangible Reels project involved Marcos Serrano; the Tangible Box' box was designed and built by Nicolas Billiotte during his internship. As for the ongoing projects that we describe in Chapter 6 and Appendix D, the name of the students or researchers that were or are involved with each project is given in the corresponding sections.

7.3 USE OF STATISTICS

Over the last two decades, the use of statistics within the HCI community has become more and more prevalent. In particular, statistics based on the Null Hypothesis Significance Testing (NHST) paradigm are widely used to analyze user studies' quantitative results. However, the use of this paradigm is criticized more and more. Since reviewing these criticisms would be beyond the scope of this thesis, we refer the reader to [44,48], and only mention some of them: 1) as compared to confidence intervals, p-values convey only a very limited amount of information (they do not indicate what is the range of plausible values) and "are unreliable and vary wildly across replications"; 2) small p-values (e.g. < .05), although they indicate a statistical significance, do not systematically indicate a practical significance (e.g. a difference of 0.2 seconds between two interaction techniques); 3) p-values are difficult to interpret and statistical tests based on NHST are difficult to understand; 5) NHST promotes dichotomous thinking.

Due to these growing concerns, the APA (American Psychological Association) [73] recommends reporting effect sizes and confidence intervals instead of p-values. As a reminder, an effect size is the measure of the magnitude of a phenomenon, or broadly speaking, "the amount of anything that is of research interest" [44] (it is usually the mean or the difference between means); a 95% Confidence Interval is "an interval calculated from sample data that is one from an infinite sequence, 95% of which include the population parameter" [44]. In this thesis, we follow the APA recommendations and systematically report confidence intervals, using the following standard notation: *best estimate* = 3.5, 95% CI [3.1, 3.9].

The user study conducted to assess the usability of the Tangible Reels interface (Chapter 3, 6) was first analyzed based on the NHST paradigm and results were published by reporting p-values of statistical tests only [51]. In this thesis, we analyzed data using estimation methods instead [44].

7.4 READING HINTS[10]

Except for this chapter and the conclusion, each chapter (and each part in Chapter 2) is framed by one introduction section and one conclusion section which summarizes the chapter/part. Chapters, sections and sub-sections are numbered with Roman numerals, but for the sake of clarity the number and title of the corresponding chapter (and part) is only indicated at the top of each page. Chapter 2 is divided in five parts and each part is identified with an upper-case letter.

Each figure caption is prefaced with the number of the chapter.

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[10] Using a PDF viewer, every term written is grey is a bookmark and the tables of contents given in the beginning of the thesis and in the first page of each chapter are composed of hyperlinked headings. The table of contents can also be displayed in the side bar of the PDF viewer.

CHAPTER 2

RELATED WORK

> *… vous devriez également évoquer sans hésiter Jean Moulin et Pierre Brossolette, car ces deux hommes n'ont absolument rien à faire dans votre ouvrage zoologique. Vous aurez donc raison de les mentionner, dans un but d'orientation, de contraste, de repérage, pour vous situer. Car il ne s'agit pas seulement de tirer votre épingle du jeu, mais de bouleverser tous les rapports du jeu avec des épingles.*
>
> Romain Gary (Emile Ajar). Gros-Câlin.

Chapter structure

Part A – Nature and use of maps and diagrams

Part B – Production and characteristics of tactile maps and diagrams

Part C – Interactive maps and diagrams for visually impaired users

Part D – Tabletop Tangible User Interfaces: properties and implementation

Part E – Designing tabletop tangible maps and diagrams for visually impaired users

Related publications

J. Ducasse, M. Macé, C. Jouffrais. *From open geographical data to tangible maps: improving the accessibility of maps for visually impaired people*. GeoVis'15. Regular paper.

J. Ducasse, A. Brock, C. Jouffrais. *Accessible Interactive Maps for Visually Impaired Users.* In E. Pissaloux & R. Velasquez (Eds.), Mobility in Visually Impaired People - Fundamentals and ICT Assistive Technologies, 2017. Springer. Book chapter.

J. Ducasse, B. Oriola, M. Macé, C. Jouffrais. *Designing spatial and tangible interfaces for visually impaired users: why and how?* IHM'16. Regular paper (in French).

Introduction to Chapter 2

Prior work related to this thesis falls into five categories:

- In **Part A**, we define the nature of maps and diagrams and their benefits as compared to non-graphical representations. We particularly discuss the benefits of maps as a tool for spatial cognition and geovisualization, and the benefits of diagrams as a tool for problem solving. Using a number of empirical and theoretical studies, we then illustrate how these benefits, although typically referring to visual maps and diagrams, are also relevant for visually impaired users.
- In **Part B** we describe the main methods of production and construction of tactile maps and diagrams and identify and compare their characteristics in terms of content, production, availability and updatability. Based on this analysis, we discuss two ways tactile maps and graphics could be improved. We also identify which aspects of the exploration of tactile graphics should be preserved when designing interactive and updatable maps and diagrams.
- In **Part C** we describe the main approaches that have been used to design accessible and interactive prototypes. To do so, we propose a new classification that distinguishes between digital and hybrid prototypes–this classification was published in a book chapter [50] and constitutes a contribution of this thesis. The review of traditional and interactive maps and diagrams indicates that the design of interactive, physical and yet updatable maps and diagrams has not been thoroughly investigated, and that tangible interaction appears to be a good candidate to fill this gap.
- In **Part D** we provide an overview of the field of Tangible User Interaction (TUI), including their benefits and limitations as well as technologies to develop tabletop TUIs.
- In **Part E**, we particularly focus on the design of tangible interfaces for visually impaired users.

PART A
NATURE AND USE OF MAPS AND DIAGRAMS

1 INTRODUCTION

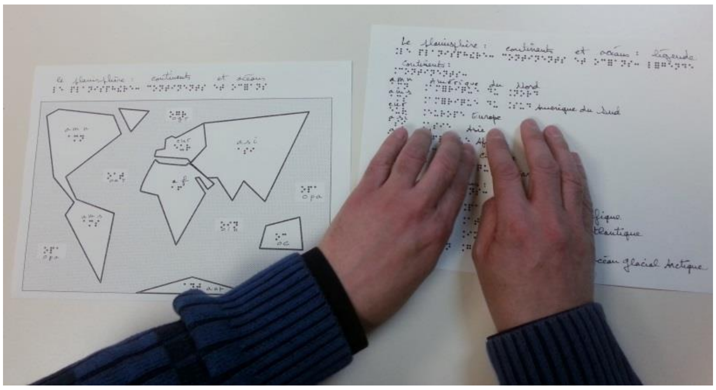

Figure 2.1. A visually impaired user is exploring a tactile map and its corresponding Braille key. The map is printed in relief so that the user can feel the different symbols, lines and areas by sweeping his/her hands above the map.

The term "graphics" encompasses a large variety of representations, including charts, maps, pictures, drawings, etc. The term "tactile graphics" itself refers to graphics intended to be read principally by touch rather than vision [1]. As an example, Figure 2.1 illustrates a visually impaired user reading a tactile map. In this first part, we define the scope of this thesis dissertation by providing an overview of existing classifications of graphics. Focusing on maps and diagrams, we highlight their benefits and report on several empirical studies that demonstrate that these benefits also hold for visually impaired users.

2 GRAPHICAL REPRESENTATIONS

2.1 CLASSIFICATION OF GRAPHICS AND RESTRICTION OF SCOPE

As we said, the term "graphics" embraces several types of representation. However, a unique classification does not exist [243,267]. In his seminal work on the semiology of graphics, Bertin [15] identified four types of graphics: diagrams, maps, networks and symbols. Later on, Lohse et al. [170] proposed to classify existing types of graphics using an empirical method. They asked twelve participants to sort forty graphics into as many clusters as they wanted. From this study, six main categories were identified, which partly correspond to those proposed by Bertin [15]: diagrams, maps, networks, icons, graphs, tables. This classification was later used and adapted by Paneels et al. [227] in their review of haptic data visualizations. The authors proposed seven categories: diagrams, maps, networks, signs, charts, tables, images. Purchase [243], in a literature review of diagram research, proposed a broader classification that distinguishes between abstract (i.e. *symbolic*) and concrete (i.e. *iconic*) diagrams. Abstract diagrams "have no perceptual relationship to the concepts that they represent"; they include networks (e.g. family trees), set diagrams such as Venn diagrams (often composed of a set of overlapping circles showing relationships between elements), and charts (including line, pie and bar charts). Concrete diagrams "have a perceptual relationship to the objects that they represent"; they include schematics (e.g. to illustrate the water cycle), arrangements of geometrical shapes to depict physical position relationships (e.g. seating arrangement) and digital images. Maps are a subtype of schematics.

Although this brief review is not exhaustive, it indicates that various classifications have been proposed and that one term may not always refer to a single type of graphical representation. In addition, it is not always obvious to know whether one diagram pertains to one category or to another. However, it seems that four categories can be easily distinguished: maps, which unlike other graphics are always associated with geographic locations; tables, which are more textual than graphical; icons or signs, which do not depict relationships between concepts but "impart a single interpretation or meaning for a picture" [169]; images or pictures, which are realistic representations of an object or a scene. Other types of graphics have been alternatively classified into diagrams, charts, graphs or networks, depending on the authors' definitions.

In the scope of this thesis, we are interested in graphics whose spatial organization is particularly meaningful, either because it maps the reality, or because it helps the user to understand the relationships between various elements. Therefore, we will focus on maps as well as on graphical representations that are not tables, icons/signs or images. We will refer to these non-geospatial graphics as diagrams, a term which must be taken in its broadest sense. Our use of the terms "maps" and "diagrams" is similar to Winn's [343], although his definition of diagrams did not encompass graphs and charts:

> *"Maps include all possible ways of representing a territory, for example: topographical maps, street plans, floor plans and schematic maps (e.g., of bus and rail systems). Diagrams include illustrations that express conceptual relationships spatially, for example: flow diagrams, schematic drawings, organizational charts, diagrams showing text structure, time lines, and family trees."*

When necessary, we will use specific terms according to the following definitions: graphs show relationships between at least one continuous and one categorical variable (e.g. line graph) [343]; charts show relationships between categorical variables (e.g. bar chart and pie chart) [343]; networks show the relationship among components (e.g. flow charts and decision trees) [169]; time charts display temporal data (e.g. a Gantt chart) [169]; cartograms are spatial maps that show quantitative data [169]. We use the term *graphic* to refer to any type of representation that is used to convey information using graphical (tactile or visual) symbols.

2.2 THE GRAMMAR OF VISUAL AND TACTILE GRAPHICS

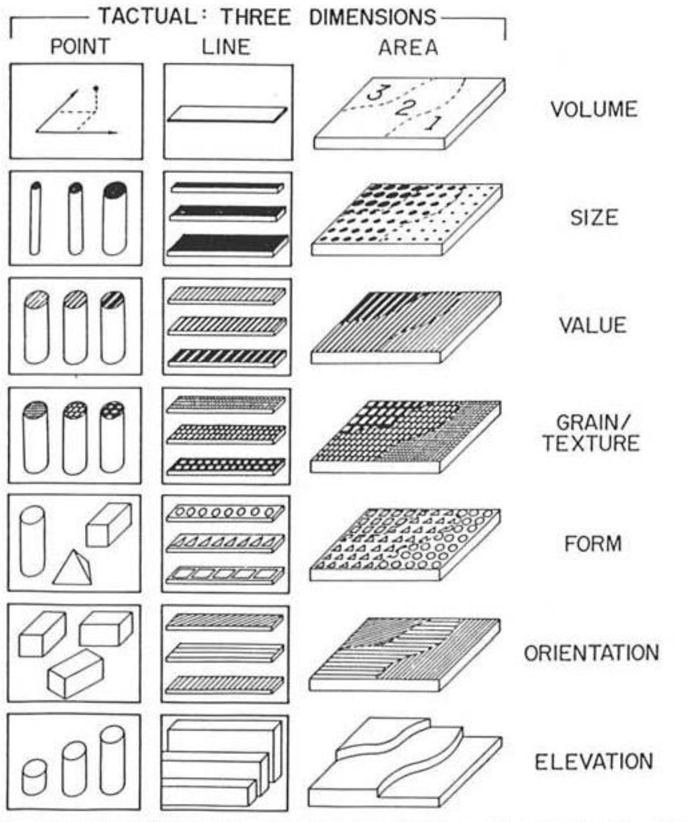

Figure 2.2. An adaptation of the six retinal variables originally proposed by Bertin [15] **into six tactile variables** [318]**. The variable "volume" is the equivalent of the planar variable "position".**

Purchase [243] stated that diagrams are "a composite set of marks (visual elements) on a two-dimensional plane". In his pioneering work Bertin [15] indicated that depending on the type of data to be conveyed, six retinal variables could be used: size, value, texture, color, orientation and shape. These variables are used in combination with two planar variables, the x- and y- positions of the element. They encode information thanks to a set of graphical marks, also referred to as *implantations*. There are three types of implantations: points, lines and areas, which therefore constitute the elementary units or *primitives* of any graphical representation. Bertin's graphical variables were later extended by McEachren [97] to include three additional ones (arrangement, textures and focus), and were also adapted by Vasconcellos [318] for the design of tactile graphics, as shown in Figure 2.2. In fact, when designing tactile graphics, visual elements must be transcribed into elements that can be perceived using the sense of touch (and, in the case of interactive maps and diagrams, with the sense of hearing). In that sense, graphical tactile variables use the three dimensions (x-, y- and z- positions) instead of the x- and y- positions only. Despite this main difference, tactile graphics rely on the same *implantations* as visual graphics: points, lines and areas.

3 MAPS

3.1 ADDITIONAL DEFINITIONS AND TYPES OF MAPS

According to Harley and Woodward [344] maps are "geographic representations that facilitate a spatial understanding of things, concepts, conditions, processes or events in the human world". The definition proposed by Montello [208] is also interesting, as it clearly emphasizes the fact that maps allow users to access spatial information that would otherwise be difficult to access, if not impossible. Montello defines four psychological spaces (i.e. space as perceived by a human) that depend on "the projected size of the space relative to the human body". *Figural space* is "projectively smaller than the body" and can be apprehended without moving. Within figural space, *pictorial spaces* are small flat spaces (i.e. maps) and *object spaces* are 3D spaces (i.e. small scale models). *Vista space* is "as large as or larger than the body" and can be apprehended without moving (e.g. town squares). *Environmental space* is "projectively larger than the body" and requires locomotion to be apprehended (e.g. cities). *Geographical space* is "much larger than the body" and cannot be apprehended through locomotion (e.g. countries). Therefore, maps are pictorial spaces that represent vista, environmental or geographical spaces.

Two basic types of map exist: reference maps (also referred as topographic maps) and thematic maps [171]. Reference maps convey general information: they are probably the most common type of maps as they include street maps such as those that can be accessed via Google Maps or OpenStreetMap. They support orientation and mobility[11] by providing the possibility to explore unknown areas, acquire an overview of the surrounding of a landmark, localize specific landmarks, or prepare a journey. Thematic maps depict specific geographic themes [171]. More precisely, they are maps "in which the distribution, quality and/or quantity of certain (groups of) phenomena or themes are represented on a topographic base » [57]. Thematic maps include but are not restricted to dot maps (e.g. each dot represents a point of interest), flowline maps (e.g. to illustrate migrations flows), choropleth maps (where the colors of the areas depend on a quantitative variable, e.g. the higher the darker) and diagram maps (where one chart is displayed within each area of the map, e.g. countries or regions) [57].

3.2 USE OF MAPS

Carter [32] identified several ways maps can be used: for general reference (e.g. to know where places are); for navigation, control or route planning; for communication, persuasion and propaganda; for planning (e.g. to develop services for those in need); for jurisdiction (e.g. with cadastral maps); to understand spatial relationships; to forecast and warn (e.g. weather maps); to compile new maps; to decorate or collect; to store information. Broadly speaking, maps act as both storage and communication mechanisms [171].

Whereas cartography has for long been seen as a process of information communication only, where "*knowledge* that already exists and that the cartographer has access to is to be *disseminated* through the map" [177], the role of maps as tools to help users construct information or generate

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[11] We will refer to reference maps intended to be used to help a person navigate as Orientation & Mobility maps.

and test hypotheses is now well documented. In this view, maps act as “a source of information or an aid to decision making and behavior in space» [177]. In fact, map uses can be defined alongside three continuums [179], as shown in Figure 2.3. They can be used to *present knowns* or to *reveal unknowns*; they can be designed for a large audience (*public)* or on the contrary be intended to be used by an individual *(private);* when interactive, they can support a *low* degree of interaction or a *high* degree of interaction. Depending on the position of map use on these three continuums the map can serve various goals: exploring, analyzing, synthesizing or presenting geographical data [179]. In simplified terms reference maps are more commonly used to present information whereas thematic maps are often used to enable users to explore geographical data.

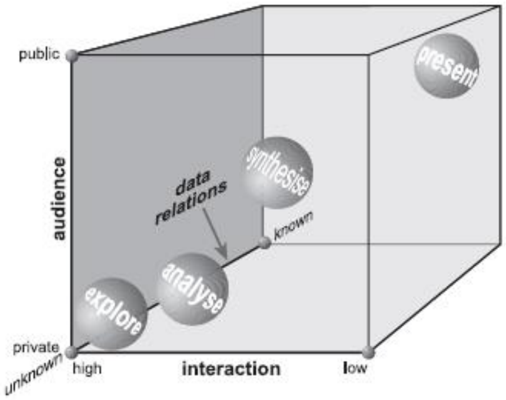

Figure 2.3. The map use cube proposed by MacEachren and Kraak [179]**, with the four map use goals.**

Depending on their use and goals, maps can have different benefits. In this section, we focus on two benefits of maps: firstly, maps can be used to understand the environment from a different perspective and therefore lead to different levels of spatial knowledge; secondly, maps can be used to “reveal unknowns”, especially in the context of exploratory cartography.

3.2.1 ACQUIRING SPATIAL KNOWLEDGE

Uttal [317] identified three ways in which the acquisition of spatial knowledge from maps by children may affect their mental representations of the external world. First, by exploring a map, one can experience the world from a different perspective than with actual navigation, which therefore makes it possible to adopt alternative ways of thinking. Secondly, when exploring a map, different kinds of information become available. In that sense, maps provide a more stable view of the space and may highlight relationships between elements instead of the elements themselves. Finally, maps allow for the use of abstract concepts such as latitude and longitude. This resonates with theories and empirical studies pertaining to the field of spatial cognition, and in particular to cognitive maps.

The term cognitive maps refer to “a person’s spatial knowledge of the environment” [142]. Research on cognitive maps has mainly been initiated by the pioneering work of Lynch [176] in which participants were asked to draw their mental images of two cities. The aim was to better understand how the structure of a city could influence its memorability and understanding. Prior to this work, Tolman [302] and Piaget [236] paved the way of cognitive mapping research by respectively studying how rats can memorize and navigate a maze [302] and how infants apprehend space [236]. Throughout the years several properties of cognitive maps have been identified. For example, distortions can be observed, be it in terms of alignment, rotation or simplification [304] or estimation of distances and directions [197].

Cognitive maps support three types of spatial knowledge: landmarks, routes and survey [282], which are usually acquired one after another. At first, landmarks are identified: they are a specific geographic location that can define from where or to where someone is going. Landmarks are also used to maintain a course during navigation. Route knowledge can be seen as a sequence of landmarks that are linked to each other. Route knowledge is mainly acquired through navigation and is dependent on the position and orientation of the user (*egocentric* frame of reference). Survey knowledge, on the contrary, does not depend on the user's orientation or position (*allocentric* frame of reference): it is similar to a bird's eye view of the environment and helps people to draw inferences between elements that cannot be experienced directly and simultaneously. In that sense, survey knowledge is considered more "flexible" than route knowledge. Spatial knowledge can be acquired through direct experience (e.g. by walking a route) and via an external media, such as verbal directions or a map. As compared to direct experience, maps present the information from a bird's eye view and therefore enable map readers to quickly acquire survey knowledge, which has a positive impact on their ability to efficiently navigate.

3.2.2 REVEALING UNKNOWNS

With the advent of Geographic Information System and visualization techniques a new field has emerged, referred to as geovisualization. Geovisualization "integrates approaches from visualization in scientific computing […], cartography, image analysis, information visualization, exploratory data analysis […], and geographic information systems […] to provide theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data" [178]. Unlike traditional cartography that is static, geovisualization allow users to prompt new hypotheses and to actively construct spatial knowledge. In that sense, maps can stimulate visual thinking and allow the readers to discover geospatial patterns, relationships and trends, or in other words, to "reveal unknowns" [149]. For example, Kraak [149] demonstrated the usefulness of geovisualization by showing how designing several versions of the famous Minard's map could lead to alternative way of thinking about the original map.

Several techniques can be provided to the users to help them manipulate the map in order to view it from different perspectives. Based on broad categories of tasks that users perform (examine, compare, order/sort, extract or highlight/suppress or filter, test cause and effect), Crampton [43] identified four types of interactivity in geovisualization:

- Interaction with the data representation (e.g. zooming in or out, panning, changing the viewpoint, remapping symbols)
- Interaction with the temporal dimension (e.g. navigation, toggling –i.e. switching back and forth between time periods to highlight changes).
- Interaction with the data (e.g. database querying, filtering, highlighting)
- Contextualizing interaction (e.g. combining data layers or juxtaposing windows)

Although reviewing the literature on geovisualization would be beyond the scope of this thesis, it is worth highlighting how innovative technologies and visualization techniques have deeply affected how maps are used, by whom, and for what purpose.

3.2.3 LIMITATIONS

It should be noted that maps are not mere representations of the external environment. When they are intended to deliver a particular message, they are designed and thought-out by cartographers so as to fit the purpose of the map. To this end, several steps are required such as data collection, edition and analysis. For example, in the design of thematic maps, only pieces of information that are relevant to the theme are presented on the map, in order to facilitate the reading process. A map is therefore the "final outcome" of these steps [171], and, as such, its content and purpose are dependent on how they were performed, and by whom. The possible differences that may exist between the reality, the message that the cartographer wants to convey and the final reader's mental representation or conception of reality have been taken into account by traditional models of cartography communication (e.g. [257]). The role of the map maker is particularly crucial for the design of tactile maps: as only a limited amount of information can be presented, the map content has to be highly simplified (e.g. curved lines are often straightened) and may not reflect the reality of its content.

As pointed out by Slocum et al. [285] individual and group differences also affect how beneficial maps can be. Influential variables include the expertise of the users, their culture (e.g. the use of different labels or the interpretation of iconic symbols), their sex, age and, obviously, their sensory disabilities. Longley [171] also pointed out that maps are based on complex rules and conventions that may not be equally mastered by all users. In fact, depending on their age, education, motivation, etc., users may have different levels of *graphicacy*, defined as the ability to use graphic displays [32].

Other limitations include the fact that maps can be used to convey incorrect information, purposely or not, and that maps that are used to display statistical information do not convey the uncertainty of the underlying data, which may lead to misinterpretations [171].

3.3 MAPS FOR WITH VISUALLY IMPAIRED USERS

Although the previously mentioned benefits were mainly identified with visual maps, Ungar [313] pointed out similar benefits for the use of tactile maps by visually impaired users:

> *"A tactile map can provide a vicarious source of spatial information which preserves all the interrelationships between objects in space but presents those relationships within one or two hand-spans. The relevant information is presented clearly (irrelevant 'noise' which may be experienced in the actual environment, is excluded); with relative simultaneity (a map can be explored rapidly with two hands and with less demand on memory); and without other difficulties associated with travel in the real environment (e.g. veering or anxiety)."*

These assumptions are based on empirical studies conducted with visually impaired children or adults. In this section we first review different methods for assessing spatial knowledge of visually impaired users, and then present two experiments that indicate how maps can help visually impaired users acquire survey-like mental representations. We then discuss the benefits of thematic maps for visually impaired users.

3.3.1 ORIENTATION & MOBILITY MAPS

ASSESSING SPATIAL KNOWLEDGE

Table 2.1. Uni-dimensional tests to assess spatial knowledge of visually impaired users, after Kitchin et al. [141]**.**

Tasks	Description
Distance	Montello identified five distance tests: *ratio scaling* requires users to estimate a distance as a ratio of another known distance; with *interval and ordinal scaling*, users are asked to compare pairs of distances (e.g. find the longer), rank distances (e.g. from shorter to longer) or assign distances to classes of relative lengths or to intervals of length (e.g. 0-100km, 100-200km, etc.); *mapping* and *reproduction* tests both require users to estimate distances, but at different scales; *route choice* tests infer distances from the answer given by the user when asked to "take the shortest route between two locations".
Direction	Users are asked to indicate the direction of a location in relation to another one using a pointing gesture or by using clock directions for example.

Table 2.2. Two-dimensional tests to assess spatial knowledge of visually impaired users, after Kitchin et al. [141]**.**

Tasks	Description
Graphic	Participants are asked to sketch the map (including landmarks and routes) on a special sheet of raised-line paper (German film[12]). Users can be asked to draw the whole map or only specific features and/or a certain portion of the map. The map can also be drawn on different sheets of papers to analyze in which order the user is sketching the map.
Completion	Some elements are provided to the users who must complete the map or fill in blank elements. To do so, users can be asked to place locations only (not routes) in relation to pre-placed locations (*spatial cued responses*); to complete sentences or maps containing blank spaces with the appropriate word name (*close procedure*); to reconstruct a model using building blocks for example (*reconstruction*).
Recognition	Users are presented with several maps or configurations and must identify the correct one. Users can also be asked to indicate whether a statement is true or false (e.g. A is located west of B).

In his seminal work, Lynch [176] assessed participants' spatial knowledge by asking participants to sketch maps. Since then, various methods have been used or suggested that can be adapted to evaluate visually impaired users' spatial knowledge. The following tables (Table 2.1 and Table 2.2) briefly describe these methods, based on Kitchin's classification [141], who distinguishes between uni-dimensional tests that "seek to uncover one-dimensional aspects of cognitive map knowledge

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[12] See Chapter 2, Part B, 2 for an illustration of a sheet of German paper.

such as distance and direction" and two-dimensional tests that "seek to produce data on a single plan"[13].

Two remarks can be made concerning landmark knowledge and graphical tests. First, these tests are particularly adapted to assess route or survey knowledge. Other tests can be used to assess landmark knowledge. For example, in her study of the usability of interactive tactile maps, Brock [24] asked participants to list the names of the streets and points of interest displayed on the map.

Secondly, to analyze sketched maps or reconstructed maps, two main methods exist. The first one consists in asking external and independent judges to evaluate how similar the sketched or reconstructed maps are with regards to the actual map, usually using a set of pre-determined criteria (see [38,320] for example). The second one, more objective, is based on bi-dimensional regression analysis and was originally proposed by Tobler [301]: it allows quantifying scale, rotation and translation differences between the sketched/reconstructed map and the actual map.

Methods for assessing spatial knowledge present several limitations. The main one is referred to as an issue of "weak methodological convergence" [143]: different results can be obtained for the same participant depending on the test that is used and/or the amount of spatial information provided to the participant in the test itself (e.g. in completion tests). To compensate for these issues, Kitchin and Jacobson [143] suggested that researchers should use multiple tests to assess knowledge, and in particular to assess survey knowledge. Another limitation is that the majority of these tests aim at measuring the accuracy of the users' mental representations, in terms of distance or direction for example. However, assessing the utility of mental representations (e.g. are users able to go from A to B) may be more relevant than assessing their accuracy. Nonetheless, indications of accuracy can be useful to better understand the nature and structure of spatial knowledge. Finally, some tests may be less adapted to visually impaired users than to sighted users. For example, sketching a map can be challenging for visually impaired users as they may rarely be as accustomed to drawing as sighted users. However, some studies reported successful use of sketching techniques (e.g. [143]).

BENEFITS OF ORIENTATION & MOBILITY MAPS

Ungar [313] pointed out that maps can be beneficial in the short term as a way to introduce a visually impaired person to a new environment. In the long term, maps can also be used to improve visually impaired users' ability to read maps, and possibly to encourage them to manipulate survey-like representations rather than egocentric representations.

As compared to direct experience, maps can be beneficial for visually impaired adults and children. For example, in a study by Espinosa et al. [60], blind adults were asked to learn a route under one of the following conditions: direct experience (i.e. walking the route); combination of direct experience and a tactile map; combination of direct experience and a verbal description of

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[13] In a previous article, Kitchin and Jacobson [143] specifically investigated tests for assessing spatial knowledge of visually impaired users. These tests were very similar to those described in Table 2.1 and Table 2.2. However, they were classified in a way that appeared to us as being quite difficult to understand, especially in comparison with the classification that they later proposed and on which we rely.

the area. They then had to walk the route unguided and to estimate the directions of landmarks. Participants performed better under the second condition on both measures, suggesting that the tactile map helped them to better understand their environment. Jacobson [118] also showed that providing visually impaired adults with a tactile map of a familiar environment can help them to get a more complete understanding of this environment.

The benefits of maps for children have mainly been demonstrated in the work of Ungar et al. [313]. In one of these studies [312] visually impaired children were asked to learn a new environment (a hall with several toys randomly placed on the floor), either by direct experience or by using a tactile map. Not only did the children manage to use the map, but “totally blind children learnt the environment more accurately from the map than from direct exploration”. Based on these results, the authors highlighted the need for blind children to be more regularly exposed to tactile maps: “If visually impaired children are trained to use tactile maps effectively, they might form the basis for improving the general spatial skills of these children and in particular the construction of cognitive maps.” [316].

3.3.2 BENEFITS OF THEMATIC MAPS

The availability and usability of thematic maps is essential, for example in the context of education [168]. However, to our knowledge, the ability of visually impaired people (whether students or not) to understand and analyze thematic tactile maps has rarely been investigated. This may be due to the fact that designing thematic maps can be particularly challenging.

To tackle this issue Lawrence and Lobben [158] investigated the design of tactile symbols for thematic tactile maps, as well as whether users were able to identify spatial patterns by reading these symbols. To do so they adapted three visual methods used for designing choropleth maps, for example by varying spacing between tactile dots to transcribe a gradation of one color. Twelve visually impaired users were then asked to explore these maps, containing two, three or four different classes and to answer three types of questions: finding a region with a specific pattern; identifying the number of classes; describing the population distribution pattern. Results showed that the proposed symbols were legible and that all participants managed to describe the spatial distribution of the population. Overall, this indicates that tactile thematic maps can effectively be used by visually impaired users.

Other studies also demonstrated that interactive thematic maps can help visually impaired users explore and identify spatial patterns. For example, Zhao et al. [352] proposed a tool that enabled visually impaired users to access georeferenced data augmented with non-textual sounds and speech output. Participants had to perform several tasks, some of them requiring the identification of spatial patterns. Results showed that participants were able “to find facts and discover data trends” – two goals of geovisualization. Other examples include the work of Delogu et al. [45] and Bardot et al. [6], where blind participants managed to answer questions about the distribution of a value across regions (respectively unemployment rates and the name of the most cultivated cereal). Weir et al. [333] also designed a weather map and reported that blind participants were able to identify trends and/or specific values such as finding which state was hotter.

4 DIAGRAMS

Research on diagrams started with the seminal work of Larkin and Simon in 1987 [155], named after the well-known proverb "why a diagram is (sometimes) worth ten thousand words". In this article the authors made a clear distinction between sentential and diagrammatic representations. Sentential representations present the information in a sequential way (e.g. a text), while diagrammatic representations use two dimensions (e.g. a bar chart). The authors described various ways in which this 2D indexing facilitates the interpretation of diagrams as well as their use in problem-solving tasks, as compared to sentential representations. Since then, further research has been conducted to investigate the benefits of diagrams in terms of cognition (see [243] for a review). In this section, we first propose a summary of the most important benefits of diagrams. Then, based on a theoretical framework proposed by Goncu et al. [84], we discuss to what extent the benefits of visual diagrams may also be relevant for visually impaired users.

4.1 USE OF DIAGRAMS

Diagrams, like maps, are external representations, i.e. "representations that are useful for problem solving and reasoning » [42]. In that sense, they may serve as memory aids by sparing the user the need to hold the information internally while manipulating or exploring it.

Larkins and Simon [155] suggested that a diagrammatic representation is beneficial in terms of problem-solving, when compared to sentential representations. More precisely, they indicated that diagrams facilitate *search* and *recognition*. When exploring a diagram, readers can quickly distinguish clusters of elements or those which are adjacent to a specific element. On the contrary, with sentential representations such as texts or lists, readers must search the entire representation to understand how the elements are related to each other. More importantly, diagrams ease *recognition* by making information explicit: "a diagram preserves explicitly the information about the topological and geometric relations among the components of the problem", making recognition "automatic and easy". On the contrary, sentential representations require the reader to mentally compute these perceptual inferences, making recognition "explicit and extensive". As an example, the authors described the following situation: a set of points can be presented using a table of x and y coordinates or a graph. The maximum value and the overall trend of the data set can be very easily recognized using the graph, but when using the table inferences have to be drawn to identify these values and patterns. Even though both the table and the graph present the same information, their representation impacts how this information is perceived and interpreted and may therefore make problem-solving more or less efficient.

Scaife and Rogers [268] proposed an analytic framework to better understand how external cognition works based on three characteristics: *representation* (structural properties), *computational offloading* (cognitive benefits), and *graphical constraining* (processing mechanisms). As we just mentioned, referring to the work of Larkins and Simon [155], the difficulty of solving a problem is dependent upon the nature of its *representation*. The notion of *computational offloading* refers "to the extent to which differential external representations reduce the amount of cognitive effort required to solve informationally equivalent problems" [267]. For example, in a study based on diagrams of electrical circuits, Bauer and Johnson Laird [9] observed that subjects performed better with diagrams than with verbal descriptions, suggesting that diagrams improved reasoning.

They indicated that the diagrams allowed the participants to "imagine moving the pieces or switches". In that sense external representations serve as a cognitive support. Finally, diagrams can help users by limiting the kind of inferences or interpretations that can be made and therefore reducing the amount of possible solutions (and errors) of the problem: this characteristic is referred to as *graphical constraining*. Although this normally applies to concrete diagrams, it is also applicable to abstract diagrams such as Euler circles [289]. By representing problems graphically, designers can therefore limit the type of errors that are possible.

Finally, in the same way that good graphicacy skills are required to take advantage of maps, graphicacy is also a critical factor in the efficient use of diagrams. Understanding diagrams requires particular skills [42] that "[need] to be learned, not assumed" [243].

4.2 DIAGRAMS FOR VISUALLY IMPAIRED USERS

Goncu et al. [84] compared similarities and differences between the (potential) benefits of tactile and visual diagrams. Overall, they acknowledged that tactile graphics could be highly beneficial for visually impaired users. However, they also commented upon several reasons why the benefits of tactile diagrams may not be as striking as those observed for visual diagrammatic representations over sentential ones. The main limitation comes from the specific properties of tactile exploration (see Part B, 5). Unlike visual exploration, tactile exploration is mostly sequential: only a limited amount of information can be perceived simultaneously and the different stimuli must be mentally integrated in order to form a global mental image. Therefore, the tactile exploration of a graphic is cognitively demanding and the whole graphic cannot be accessed "at a glance".

Such limitations may therefore restrict the benefits of *computational offloading* and of *graphical inferences* as the user will still have to search for elements, in order to compute inferences mentally and to mentally "visualize" the whole graphic instead of simply "looking at" it. The authors also pointed out that the benefits of 2D indexing may be impaired by the use of a Braille key. In fact, as we will see in Chapter 2, Part B, 3.1, tactile diagrams often come with a Braille key that requires users to switch back and forth between the diagram and the key. Therefore, even if elements are grouped together, their exploration may be disrupted by the fact that users will need to switch to the Braille key in order to understand what the elements represent. However, it may be hypothesized that once the user has read the key a sufficient number of times, they do not need to use it anymore and the exploration may be less disrupted.

Despite these limitations, tactile diagrams very likely facilitate *search* and *recognition* as compared to a non-visual sentential representation such as a table accessed with a screen reader. Wall and Brewster [328] interviewed four visually impaired users to better understand which aspects of tactile diagrams were important to them. They observed that users swept their hand over the diagram in order to gain an "overview" of the diagram; such a strategy can facilitate *search*. The authors also gave examples of diagrams where axes were "highlighted" using a particular tactile pattern. This certainly facilitates *search* (the user can quickly relocate the axes) as well as *recognition* (e.g. users can quickly identify the type of diagram). Visually impaired users also used their finger to "mark the data" and make it easier to relocate a point. Once again, such methods facilitate *search* and *recognition*, and, more generally, *computational offloading*. Finally, because tactile diagrams often preserve the layout and structure of visual diagrams, “topological and geometric relations among the components of the problem” are also preserved, facilitating *graphical inferences*.

It is worth noticing that Wall and Brewster [328] also reported that participants had difficulties to go « beyond the data »: for example, participants found it very difficult to estimate how much higher bar 2 is compared to bar 1, if bar 2 is doubled. Such observations suggest that participants did not know which strategy to use to answer the question, which may be due to a lack of training and/or exposure, once again emphasizing the importance of *graphicacy*.

5 CONCLUSION OF PART A

In this part we restricted the scope of this thesis to the study of maps and diagrams. Maps represent vista, environmental or geographical spaces whereas diagrams express conceptual relationships spatially. In this thesis, we do not consider other types of graphical representations, such as tables, icons/signs and images. Both maps and diagrams, whether visual or tactile, are composed of a set of marks. Each mark can be characterized by one or several graphical variables such as a particular size, shape or orientation and can be one of the three possible *implantations*: a point, a line or an area. Two basic types of map exist: reference maps are more commonly used to present knowns whereas thematic maps are more often used to reveal unknowns. We showed that for both sighted and visually impaired users, maps are very useful to help users build survey-like (or *allocentric)* mental representations instead of route-like (or *egocentric)* mental representations. They can also be very useful to help users discover spatial trends, especially if they are interactive. Diagrams present several advantages when compared to sentential representations (e.g. a verbal description): they facilitate *search* and *recognition* by enabling users to access all the pieces of information simultaneously. Therefore they act as external representations which lower the need to draw inferences mentally (*computational offloading)* while reducing the type of errors that can be made (*graphical constraining)*. Such benefits can be less striking for visually impaired users as the inherent properties of tactile perception make it impossible to access a whole diagram at once. Nevertheless, it makes possible for visually impaired users to quickly explore, compare and relate different parts of the graphs, especially when they can explore the diagram with their both hands. For all these reasons, maps and diagrams appear to be as essential for visually impaired users as they are for sighted users, and therefore the former should have an equal access to these types of representations. In the next part, we describe the current means of production of tactile maps and diagrams, as well as their advantages and limitations.

PART B

PRODUCTION AND CHARACTERISTICS OF TACTILE MAPS AND DIAGRAMS

1 INTRODUCTION

In this second part, we first describe how tactile graphics are normally produced, starting with a brief history. Unlike visual graphics, which have become more and more omnipresent with the development of the web, tactile graphics still rely on specific technologies that are not widely available and/or on hand-crafted techniques that require the presence of a sighted person. We then discuss the characteristics of tactile maps and diagrams, focusing on their content, means of production, availability and updatability. Secondly, we discuss two ways that could overcome their inherent limitations: automating their production (or at least providing tactile graphic specialists with suitable software) and making them interactive and more updatable. In the last section, we focus on the exploration of tactile maps and diagrams. In particular, we highlight how the physicality of tactile graphics is essential to support efficient strategies for retrieving and encoding spatial information that rely on multiple hand/finger exploration. By doing so, we aimed at defining important notions pertaining to the field of tactile perception that should be taken into account when designing maps and diagrams for visually impaired users.

2 A BRIEF HISTORY OF TACTILE GRAPHICS

> "*Down to the epoch when M. Weissembourg, of Mannheim, made maps in relief, the lessons of geography given to the blind were merely oral; consequently, they had made very little progress in that study. The first attempts of M. Weissembourg were not happy. He began by having the principal divisions of Europe engraved in relief, on a board of the size of ordinary maps […] and this defective plan was abandoned almost as soon as formed. […] He also made maps, at a great expense, which excited more curiosity than interest, and were much spoken of at the time: the seas and rivers were represented on them by pieces of glass, cut with great art, and the different countries were distinguished by sand of different granulations; the towns were known by copper nails with round heads of different sizes: but the rubbing soon made the sand disappear, and [these maps] were of no use to those who had their sight, who could not even guess the purpose of them unless informed of it.*"
>
> An essay on the instruction and amusements of the blinds,
> Doctor GUILLIÉ, first published in 1819 [91].

Attempts to make graphics accessible to blind people can be traced to the middle of the 18th century. As shown by the excerpt below, these attempts have not always been successful. Levy [166] reported that Weissembourg was the first to try producing "suitable maps for the blind", using embroidered cloth and other hand-crafted materials. Valentin Haüy, the founder of the first school for visually impaired people in 1784, as well as the inventor of the embossing printing machine, was one of the first who thought of teaching his students geography by using wires to represent borders and nails to represent towns and islands [354]. A similar technique was used to teach mathematics and was supposedly inspired by a blind mathematician who used pegs (inserted into a board) and thread to represent various figures [166]. In 1837, Samuel Gridley Howe, founder and president of the future Perkins Institute, produced an entire atlas of the USA, using a new embossing method[14]. Two years later, the first tactile map was created in the UK for the Glasgow Asylum for the Blind [207]. Although tactile maps were produced at a larger scale by a few specialists such as Kunz in Germany and Klemm in the United States [59], the production of tactile graphics required high "hand-crafting" skills for a long time–and still does. For example, in 1890, the New York Times reported that maps were made accessible to the visually impaired users thanks to "dissected maps", i.e. maps which were carved in the wood and separated into several pieces, creating a puzzle that the students had to solve [353].

Tatham identified three main developments that improved the way tactile maps (and diagrams) were produced [297], which are illustrated in Figure 2.4. The first was "the use of the spur-wheel to create non-textual features on Braille paper". This tool allows people to quickly create tactile graphics, albeit with limited precision and resolution (Figure 2.4, left). The second development was the production of collage maps using raw materials such as strings, cardboard, paper (see Figure 2.4, middle), fur, sandpapers, etc. This type of collage maps has been particularly well documented by Edman [56]. The third development was the use of German film, a transparent plastic sheet that must be placed on a rubber mat before being drawn on using a stylus or a pen. When drawing, a raised image is created that users can immediately feel (Figure 2.4, right).

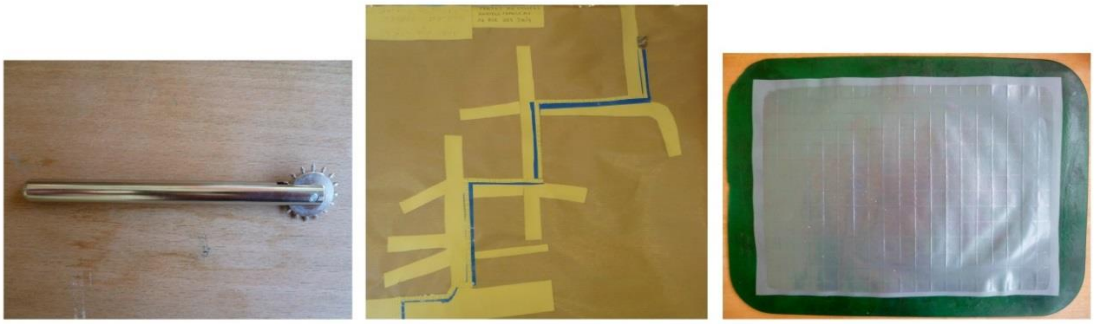

Figure 2.4. Three main developments for tactile maps and diagrams. Left: the spur-wheel can be used to draw tactile lines. Middle: collage maps made out of various textures. Right: German film (with a grid) placed on a rubber mat.

According to Tatham [297], "the tactile equivalent of the printing revolution occurred in the 50 or so years since the end of the second world war". In fact, two technological developments emerged and deeply changed the way tactile graphics were made: thermoform machines (which became a standard technique in the 1960s [100]) and microcapsule fusers (particularly used from the 1980s [100]). In particular, Ungar [311] stated that the affordability and availability of these two technologies contributed during the 1980s to a growing interest in research for tactile graphics (production, perceptual and cognitive processes involved in exploring a tactile document, readability of tactile symbols, etc.)

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[14] http://www.davidrumsey.com/blog/2012/5/21/atlas-for-the-blind-1837

Today, collage maps based on hand-crafted techniques are still used, but tactile graphics specialists prefer to use technological methods of production. Furthermore, during the last decade, inkjet and 3D-printing have also emerged as a new way of producing tactile graphics. In the following section we briefly describe these techniques: embossing, thermoforming, swell paper, inkjet and 3D-print. We also describe two techniques that are mainly used by visually impaired students to construct their own maps and diagrams, referred by Edman [56] as graphics with "movable parts", as opposed to "static" tactile graphics that cannot be updated once printed.

3 CURRENT PRACTICES

Designing a tactile map is a complex and time-consuming process that requires tactile graphics specialists, sometimes also referred to as transcribers. According to the Braille Authority of North Canada [299], a tactile graphics specialist must first select the information that will be presented on the tactile graphic, and possibly simplify or reorganize it so that it may be spread over several sheets. Each element of the original (and usually visual) graphic needs to be categorized into one *implantation:* point, line or area. The elements are then created using a specific tactile symbol, trait or texture. The resulting graphic generally consists in one title and the tactile map or diagram upon which Braille abbreviations are displayed. The Braille legend is usually presented on a separate sheet.

3.1 STATIC TACTILE GRAPHICS

3.1.1 METHODS OF PRODUCTION

Embossed maps and diagrams are produced with a Braille printer or embosser that punches dots into paper, similar to Braille dots. Using this technique it is possible to create a variety of graphics that can easily be read by a visually impaired user. However, their resolution is limited, the height of the dots cannot vary much, and they are not visible to a sighted person [325]. Finally, a braille embosser is expensive [23].

Figure 2.5. Left: a hand-crafted master used for thermoforming. Middle: a map of France made with thermoforming. Right: a raised-line line graph and a raised-line map of France, made with swell paper.

Thermoforming consists in placing a sheet of plastic upon a hand-crafted master made of different textured papers (a collage map or diagram, see Figure 2.5, left). When heated in a vacuum, the plastic sheet is shaped by the mold and permanently deformed (Figure 2.5, middle). The main advantage of thermoforming is that it allows varying heights and textures by using a master composed of different materials. Also, because thermoformed maps and diagrams are made out of plastic, they are durable. Creating the collage master is time-consuming and requires specific skills. However, once the master has been created, it can be reused to print several copies of the graphic.

Swell paper or microcapsule graphics are printed on a special heat-sensitive paper (called swell or microcapsule paper) containing microcapsules of polystyrene, using a normal printer. When the sheet passes into the heater, printed parts in black are heated at a higher temperature than non-printed parts, making the microcapsules under the ink swell. This creates a relief that the user is able to feel (Figure 2.5, right). Using this technique various patterns can be printed but their height cannot vary. This type of graphic is well appreciated by visually impaired users and can also be perceived by sighted users [23]. Nowadays it is also possible to print colored swell-paper graphics, which is extremely useful for people with low vision. Because the maps and diagrams can be printed using a normal inkjet, their reproduction is relatively easy. However, the heat-sensitive paper is not very durable and these graphics need to be reprinted after a number of uses. Maps and diagrams produced with this technique are often referred to as **raised-line maps and diagrams**.

New inkjet technology allows the production of durable graphics. To produce these graphics, an "acrylic polymer ink is repeatedly printed onto a thermoplastic substrate and exposed to ultraviolet light which bonds the ink to the substrate and cures it solid" [190]. This allows for the production of patterns of various heights as well as a greater variation of symbols, lines and textures. These graphics are also visible by a sighted person. Although extremely promising, this technology is not yet widely used [212].

Finally, **3D-printed graphics** can also be created. Similar to new inkjet technology, they allow for a great variation of patterns as well as for various heights (Figure 2.6). 3D-printing is relatively slow and is limited to a small area, which might make it necessary to print parts of the graphics separately [324]. However, recent improvements allow for the creation of light yet durable graphics with fine details [298].

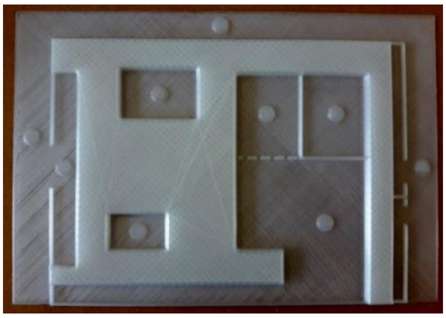

Figure 2.6. A 3D-printed map of the IJA[15] with elements of various heights. (Made by Théophile Vier during his internship.)

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[15] Institut des Jeunes Aveugles (Young Blind's Institute), Toulouse, France.

3.1.2 CHARACTERISTICS

Due to technological and perceptual constraints (cf. following section), the **content** of a tactile map or diagram is limited and it is not possible to simply translate any element of a visual graphic into a tactile element. Content must be adapted and simplified [299]. For example, whereas visual lines can support several variations (color, thickness, pattern, opacity, etc.), for tactile lines it is recommended that no more than five different types of line should be used on a tactile document [21], which makes them less expressive. The number of different textures that can be used on a document is also limited, which restrict their complexity[16]. To compensate for this limitation, teachers we are working with indicated that students are progressively introduced to different textures. However, since a tactile map cannot be readily updated, several versions of the same map are used to introduce a limited set of textures (1-3) each time. The use of several tactile documents may also be necessary when the original document contains too many pieces of information. Another limitation in terms of content is the use of Braille labels [23]. Because they take up a lot of space, the tactile document can quickly become too dense to be efficiently perceived by touch. Therefore, Braille abbreviations are often used in combination with a Braille key that may be presented on a separate sheet, further increasing the number of documents used. The use of Braille labels is also an issue because less and less visually impaired users know how to read Braille [214].

Another aspect is worth noting, which we will refer as *bi-graphism*[17]. Tactile diagrams are intended to be read by visually impaired users, each of whom have different abilities to perceive visual elements and/or colors depending on their degree of blindness. For users with low vision, it is important for the graphic to be tactile but also visual so as to take full advantage of their perceptual abilities. For these users strong contrasts between colors may be very helpful (Figure 2.7). Another advantage of making visual and tactile graphics is that they can be used together by a visually impaired and a sighted user (e.g. a sighted teacher and a blind student). The above-mentioned methods of production support the creation of visual and tactile maps and diagrams at different levels.

Figure 2.7. A "bi-graphic" raised-line map with several visual elements used at the IJA. (Made by Celia Pieruccioni during her internship.)

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[16] As we said in [5], we make the distinction between "complexity" (the number of elements / the amount of data) and "expressivity" (the nature of the elements being represented). For example, swell-paper maps are more expressive than embossed maps because different line patterns and textures can be used, but they are not necessarily more complex.

[17] This term is used by some teachers and transcribers working at the IJA but we could not find a translation in the literature.

In terms or **production**, correctly transcribing a visual document into a tactile one or creating a tactile document from scratch requires particular skills and knowledge about the perceptual aspects of tactile exploration. Consequently, to access a map or a diagram, a visually impaired person must rely on a sighted tactile graphics specialist. Besides, whereas some of the above mentioned production techniques are particularly suitable for the replication of existing diagrams (e.g. thermoforming and swell-paper), others are less adapted as they require more time (3D-printing and inkjet technology) [212].

Although educational centers employ professionals, the needs of the visually impaired students cannot be entirely fulfilled as they would require the adaptation of whole textbooks. Outside school, tactile maps and diagrams are very rarely available. This lack of **availability** is also due to the fact that creating a tactile map or diagram is time consuming and expensive, notably because of the specific material that must be purchased. Klatzky et al. also pointed out that tactile graphics "are single-purpose, and their physical bulkiness and weight reduce transportability and impose demands on storage space" [144]. Such issues may further account for a lack of availability of tactile maps and diagrams.

In terms of **updatability**, tactile graphics are static, meaning that once printed, their content cannot be modified. As we noted earlier, a new tactile document must be printed whenever a teacher wants to introduce new elements on the map. These elements cannot simply be added to the first document. This lack of updatability limits how tactile maps and graphics can be used, especially in the context of learning. It also makes tactile documents quickly outdated. For example, on an Orientation & Mobility map, transitory obstacles such as roadworks cannot be displayed unless the whole map is reprinted.

3.2 UPDATABLE GRAPHICS[18]

Static tactile maps and diagrams are produced by a tactile graphics specialist and accessed by a visually impaired user. In some cases, however, allowing users to produce their own maps and diagrams can be highly beneficial. For example, in [195], the authors pointed out that when children are discovering the concepts of graphs or charts, it is essential to let them make mistakes and correct them. Also, even if tactile maps do not need to be regularly updated, charts and graphs do: in this case, having a way to quickly update the graph is very useful. Static tactile maps and diagrams support neither the construction nor the edition of spatial content. However, it is possible for visually impaired students to construct their own maps and diagrams using a magnetic, cork or self-adhesive board [59], as well as a sheet of German paper, as we previously discussed.

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[18] Updatable graphics are similar to what Edman [56] described as « graphic with movable parts », in opposition to static tactile graphics.

3.2.1 METHODS OF CONSTRUCTION

Magnets are more often used by Orientation & Mobility[19] teachers to help a student learn an itinerary (see Figure 2.8, left). To prepare a new itinerary for the students, the teacher builds a simplified representation on a magnetic board: every time a new magnet is placed on the board, the teacher indicates what it stands for and lets the student touch it. After walking the route, the students may be asked to rebuild the route so that the teacher can check whether it has been understood. Magnets are also used to represent more complex spatial configurations such as road crossings or floor plans.

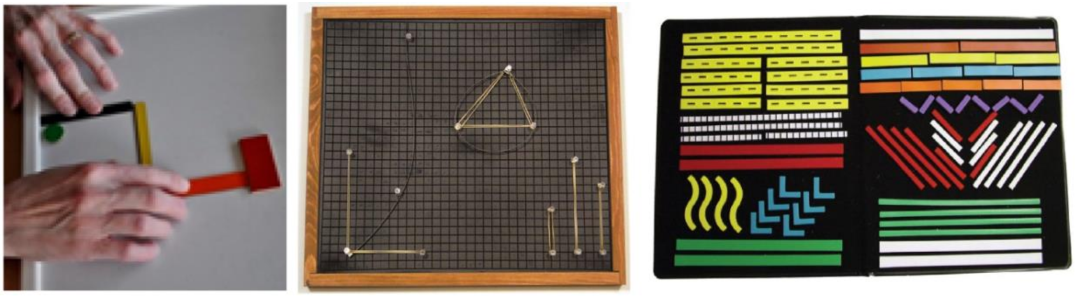

Figure 2.8. Left: magnetic board. Middle: cork board mounted with a rubber mat embossed with a grid. Right: a felt-covered board with a set of pieces equipped with VELCRO®. Board pictures retrieved from https://shop.aph.org.

A **corkboard** can also be used to enable students to construct and manipulate their own charts or graphs (Figure 2.8, middle). The use of this technique has been thoroughly described in [182,195,196]. A raised-line grid is placed above the corkboard; pins are inserted and linked together with rubber bands to create line graphs or geometric shapes, for example. Limitations of this technique include the sharpness of the pins, the difficulty to pull the rubber bands over two pins and the fact that rubber bands can easily be detached.

Edman [56] also reported the use of **self-adhesive displays** based on Velcro (Figure 2.8, right). The coarse surface is mounted on a board while the self-adhesive strips are fixed to the elements (such as geometrical shapes). Therefore these elements can be quickly and easily added or removed from the board. Similarly, Wikki Stix[20] are sometimes used: they consist in "twistable wax-covered strings that easily stick to each other and to any smooth surface » [36] and that can be used to draw a physical graph very quickly.

Finally, it should be noted that 3D-Printing also enables the creation of graphics with movable parts, a feature that has mainly been investigated for the design of tactile books or pictures for visually impaired children (e.g. [136]), or for small-scale models that can be reconfigured (Figure 2.9).

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[19] Orientation & Mobility is « is a profession which focuses on instructing individuals who are blind or visually impaired with safe and effective travel through their environment" (https://en.wikipedia.org/wiki/Orientation_and_Mobility)

[20] http://www.wikkistix.com/

Figure 2.9. Two small-scale and reconfigurable 3D-printed models, used at the IJA. (Photographies by Nathalie Bedouin.)

3.2.2 CHARACTERISTICS

In terms of content, the limitations mentioned for static graphics are also true for these constructed graphics in an even more important way. Magnets or self-adhesive elements are relatively big, and so only a limited amount of elements can be placed upon the board. As for the corkboard technique, the use of pins and rubber-bands makes it difficult to construct complex diagrams. Also, unlike traditional methods of production, these methods of construction do not support a large variety of symbols, lines or areas and therefore are not very expressive. For example, with the corkboard technique areas cannot be represented using different textures; with the magnetic board lines simply consist in rectangular magnets whose textures do not differ from one magnet to another. However, maps and diagrams constructed with these methods can be perceived by a sighted person. A downside is that because the graphic is constructed in an unprepared manner, no Braille key can be provided.

To place the objects (whether pins or magnets) in their right place, students must either have a raised-line model to reproduce or be guided by their teacher [195]. Similarly, students cannot detect if their map or diagram is incorrect (e.g. when a rubber-band is detached) and must rely on their sighted peers. These constraints make this type of graphic unsuitable to be used outside school and therefore not widespread, despite the fact that they are very cheap [195].

In fact, the main advantage of these constructed graphics is their updatability, which can be used to support learning-by-doing activities. Magnets or pins can be added, removed or moved relatively easily, even if the practicability of the materials used may be questionable (see [195] for a detailed analysis of the use of corkboard and pins by a visually impaired student). Although it has not been measured, simply moving a pin to change a value on a bar chart is certainly quicker and easier than producing and printing a new version of a tactile chart.

3.3 SUMMARY OF EXISTING TACTILE GRAPHICS

Tactile graphics are mainly limited by the number of elements that they can present, and differences exist between static and updatable graphics. On one hand, static graphics can use a variety of symbols, lines and textures to make relatively expressive representations accessible (i.e., which can convey pieces of information of different nature). For these graphics the number of elements that can be represented (i.e. their complexity) is mainly limited by the properties of the sense of touch (see following section), by the method of production (e.g. Braille embossers allow fewer variations than thermoformed machines), and by the fact that Braille labels are required. On the other hand, the number of elements that can be conveyed by an updatable graphic is mainly limited by the material used (size of the elements and/or practicability), but this limitation is an important one and these graphics are usually very simple. Therefore, current practices support either the production of graphics that can convey relatively complex and expressive information but cannot be updated, or the production of graphics that can be updated but are relatively simple and not expressive.

Another distinction can be made: static graphics cannot be updated but they can easily be stored for later use. Although this can be seen as a drawback (storage issues), it can also be beneficial for users who want to regularly access a tactile document (a diagram used by a teacher every year to illustrate a particular concept, a map of the city in which a visually impaired person lives, etc.). On the contrary, updatable graphics cannot be stored as they need to be dismantled after each session so as to clear the board for other students. In [195] the authors reported that "all current techniques to construct graphs have issues. They are either non-permanent and cannot be retained, or are so permanent that they cannot be modified". Such a sentence could easily be extended to sum up what we just described: all current techniques to produce/construct maps and diagrams have issues; they are either non-permanent and cannot be retained, or are so permanent that they cannot be modified.

4 PERSPECTIVES FOR IMPROVING TACTILE MAPS AND DIAGRAMS

To improve tactile maps and diagrams, several approaches have been considered. For example, research has been carried out on the legibility of tactile symbols (e.g. [225]), and methods of production have been compared, notably in terms of users' preferences [259]. In this section we first focus on how the production of tactile graphics could be, if not fully automatic, at least computer aided. Such a process could enable tactile graphics specialists to produce more graphics, which will therefore become more available [39,253]. In the second section, we consider how making maps and diagrams interactive could be beneficial and possibly support the development of updatable maps and diagrams.

4.1 COMPUTER-AIDED PRODUCTION OF MAPS AND DIAGRAMS

Several prototypes have been designed to help tactile graphics specialists quickly and easily produce tactile maps. This was in line with the work of Lobben [168], who interviewed seven Orientation & Mobility instructors. All of them considered that it would be "beneficial […] if computer production of tactile maps was available in a simple, more accessible manner" and they all "consider using software designed specifically for the production of tactile maps". Among research projects aiming at the (semi) automatic creation of (interactive/tactile) maps, two main approaches can be identified: 1) using open source database or projects (such as OpenStreetMap[21]) to retrieve data, filter it and produce an adapted map or diagram; 2) applying image recognition algorithms to a visual map in order to transcribe it into an accessible map.

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[21] http://wiki.openstreetmap.org/wiki/Main_Page

4.1.1 USING OPEN SOURCE DATA

The Talking TMAP project was one of the first projects that proposed automatic map creation based on a Geographic Information System (GIS) [200]. It included the possibility of ordering raised-line maps on the internet or by telephone. The user needed to possess the corresponding touch device ("Talking Tactile Tablet"), to load a digital map and then place the map overlay on the display. Consequently, Watanabe et al. [330] proposed an adaptation for Japan and other regions, called tmacs. Maps produced with tmacs were later evaluated [206] and proved efficient to assist a blind person walking an unknown route. OpenStreetMap, an open-source collaborative project, was later used for similar projects (e.g HaptoRender[22]), as well as to facilitate the production of interactive (tactile) maps (e.g. [128]). Using OpenStreetMap data is particularly interesting since in 2011 it contained 30% more pedestrian roads than a commercial Geographic Information System [215]. For example, Götzelmann [87] used OSM data to automatically generate tactile maps whose content was adapted to visually impaired users and that could be 3D-printed. Users could thereafter explore the map in an interactive manner (see Chapter 2, Part C, 4.1.2). Diagrams can also be adapted from existing SVG files, which can be particularly useful to make online graphics accessible (e.g. [70,150]).

4.1.2 USING COMPUTER VISION ALGORITHMS

As for the second approach, Wang et al. [329] developed a system that automatically transcribed a map image into a tactile graphic, using optical character recognition and graphic simplification algorithms. The resulting map was immediately printable with a tactile printer and could be placed upon a tablet that displayed the softcopy of the map, once again allowing the user to explore the map in an interactive manner (see Chapter 2, Part C, 4.1.1). Similar projects for maps include [148] and [295], a project that applied computer vision algorithms to hand-drawn (and therefore easy to customize) maps. Concerning the production of diagrams, Ladner et al. developed the Tactile Graphic Assistant (TGA) [123,153], which aimed at helping professionals translating tactile graphics "much more quickly and in larger volumes (whole books at one time) [153]". The TGA took scanned images as input and applied a series of processes including image processing, optical character recognition and machine learning in order to produce an XML file that could be processed by a Braille printer. Similar projects included notably the TACTile Image Creation System (TACTICS) [331,332], which outputs swell-paper graphics. Interactive diagrams can also be created. For example, TeDUB (Technical Drawings Understanding for the Blind) [234] used image processing algorithms to adapt the content of node-links diagrams and the resulting output could be accessed using a force-feedback device.

4.1.3 AUTHORING TOOLS FOR INTERACTIVE MAPS AND DIAGRAMS

In the framework of the AccessiMap project, an open-source web-based editor based on OSM data is currently under development [52]. Unlike other projects, it provides tactile graphics specialists with an authoring tool that enables them to choose and specify the interactions required to explore the resulting tactile map (e.g. single-tap or double-tap, menus, etc.). Although this tool initially aims at facilitating the production of maps, it can also be used for the production of interactive tactile diagrams.

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[22] http://wiki.openstreetmap.org/wiki/HaptoRender

4.1.4 POSSIBILITIES AND PITFALLS

Automating the adaptation of visual content is a very promising area for making maps and diagrams more accessible to visually impaired users, and we mentioned several projects whose results are extremely encouraging. However, there are some limitations to this process. For complex representations such as maps it is very unlikely that the process could be fully automatic and the expertise of a tactile graphics specialist will remain necessary. However, by helping them throughout the adaptation process, the production of maps and diagrams can be less time-consuming and therefore a larger amount of documents can be produced. For example, with TGA, the average time to translate one diagram required less than 10 minutes, which was far less than the normal time taken [123].

For most simple maps and diagrams the process can sometimes be fully automatic. For example, the Talking TMAP Project was particularly efficient at adapting visual maps [201]. This is probably due to the fact that the maps used were mainly composed of very symmetric street systems, as are typical in North America. In addition, some types of diagrams can be very structured, such as line and bar charts. For these diagrams, applying recognition algorithms is certainly easier, for example to quickly identify the x- and y- axes. However, even if the process is automatic, results may not always be satisfying. For example, with the TGA prototype, issues could arise with the translation of images containing mathematical texts or with the position of the Braille labels [123].

Overall, taking into account the considerable progress in terms of computer vision algorithms (notably for optical character recognition) and the increasing development of open-source data (and especially of OpenStreetMap), progress in the field of automatic translation or adaptation of content is inevitable and will undoubtedly contribute to the greater availability of maps and diagrams. As we noted, this is particularly interesting as it could allow visually impaired users to independently access maps and diagrams. It also enables the creation and authoring of interactive content which is in line with the increasing amount of interactive maps and diagram for visually impaired users, and could also facilitate the production of updatable graphics.

4.2 INTERACTIVITY AND UPDATABILITY

As we noted earlier, the number of elements that can be presented on a static graphic is constrained by the use of Braille labels or abbreviations that take up space. With interactive prototypes Braille labels can be replaced by audio labels: not only is this beneficial in terms of content, as Braille labels can be removed, but it also facilitates the exploration process as users do not need to switch back-and-forth between the tactile document and the Braille key. It is also very helpful as a way to make maps and diagrams accessible to visually impaired users who do not read Braille.

For updatable maps and graphics, interactive features could enable users to construct and edit their graph without the help of a sighted person, therefore making them independently accessible. For example, users could be guided to place the objects in their right place and could be notified whenever an object is misplaced. A drawback of updatable graphics is that they cannot be retained [195]: however, if interactive, the content of the constructed maps and diagrams could be saved for later use. The board would still need to be cleaned but users could access their graphics by reconstructing them or by displaying them with a specific device.

More generally, interactive maps and diagrams can offer a variety of features that can facilitate and enrich the exploration process. In Chapter 2, Part A, 3.2.2, we described four types of interactivity that can be used with digital content [43]: interacting with the data representation (e.g. panning and zooming); interacting with the temporal dimension; interacting with the data (e.g. filtering); contextualizing interaction. Even though such features may be challenging to implement for visually impaired users, they remain very interesting and open several perspectives, for example in the context of learning.

5 EXPLORING TACTILE GRAPHICS

In this section, we first set out the basics of tactile perception. Understanding how the sense of touch works is important to better understand why tactile documents need to be highly simplified compared to visual ones, and what are the rules of thumb that must be respected when designing interactive maps and diagrams. It is also important to identify which aspects of the exploration of tactile graphics are beneficial (from a perceptual and/or cognitive perspective) and should be preserved–and if not, compensated for–when designing interactive map and diagrams.

5.1 TACTILE PERCEPTION

In comparison with the visual system, the haptic system is not well suited for spatial exploration and is more effective at processing the material characteristics of surfaces and objects [159]. The haptic system relies on two afferent subsystems: the *cutaneous* system and the *kinesthetic* systems. Mechanoreceptors and thermoreceptors embedded in the skin provide *cutaneous* inputs while the muscles, tendons and joints provide *kinesthetic* inputs [159].

The visual system does not require physical contact and has a large field of view as well as a high spatial resolution; this enables sighted subjects to apprehend a large amount of information simultaneously. On the contrary, during the exploration of a tactile graphic, the cutaneous system only acquires information when the users' fingertips and/or palms are in contact with the surface of the tactile graphic [84]. In addition, the spatial resolution of touch is limited: for blind subjects, there must be approximatively 0.2 mm between two points to be identified as distinct [144]. Combined with the small size of the finger pads, this indicates that only a limited amount of information can be perceived simultaneously. In fact, Loomis et al. [172] showed that exploring a raised-line drawing with one finger only (i.e. one point of contact) is similar to exploring a visual drawing with a narrow field of view (the size of a fingertip).

When exploring a tactile graphic, visually impaired users must therefore compensate for these limitations (small field of touch and limited spatial resolution) by moving their fingertips across the surface [144]. The exploration of a tactile graphic is thus sequential and requires users to integrate tactile stimulus over time and space in order to form a global mental image of the graphic. Although this process may appear similar to mentally integrating inputs across fixations resulting from saccadic eye movements, empirical studies show that the haptic system is not efficient at doing so [144]. For example, in the study by Wijntjes et al. [339] blindfolded participants were asked to explore a tactile drawing. Those who were unable to recognize the raised-line graphic managed to do it after they sketched the drawing and visually inspected it. This means that although participants had sufficient pieces of information to identify the drawing, they were not able to put the pieces together. Similarly, in the experiment proposed by Loomis et al. [172], recognition accuracy was similar between the touch condition (one finger) and the visual condition (narrow field of view), suggesting that even with vision, mentally integrating inputs that are not simultaneously perceived is a challenging task. In addition, tactile exploration can also lead to distortions or illusions such as identifying curved lines as straight [265] or underestimating the length of lines that are tangential to the body [35]. Finally, in order to integrate inputs over space, subjects must also rely on the kinesthetic information obtained from the muscles, joints and tendons. To do so a frame of reference is required, be it body-based, movement-based or external [203].

Overall, tactilely exploring a graphic is a sequential and therefore slow process. Also, because mental integration over time and space is necessary, it is also a process that is cognitively demanding [219]. This is especially true since the haptic system does not have an equivalent to peripheral vision [84]: with vision, elements that do not fall within the fovea can still be perceived by the subjects, enabling them to focus on a part of the graphic while perceiving the other parts; with touch, elements that are not in contact with the users' hands and fingertips "disappear" from their field of touch and must be stored in memory. This further complicates the exploration of tactile graphics.

Despite these limitations, the haptic system is efficient in identifying the orientation of lines as well as textures [144]. In fact, when exploring a tactile line, visually impaired subjects are able to determine its orientation using one finger only. This enables them to easily follow line contours and facilitate integration as the users do not need to search for the remaining part of the line. Rosenbaum et al. [258] demonstrated that people can even track two moving points that each trace different patterns (e.g. a circle and a square) using one finger from each hand. In addition, the spatial resolution of touch is sufficient enough to enable subjects to distinguish and characterize various textures in terms of roughness, smoothness, etc. [159]. To identify textures, hand movements or surface movements are required. Empirical studies indicate that the minimum tactually discernible grating resolution is 1.0 mm [332]. In fact, the gap between the elements that constitute the surface (i.e. groove width) can be used as a predictor of how much a texture is perceived as "rough" [161].

Both the perceptual characteristics of the sense of touch and the highly demanding cognitive process associated with the exploration of graphics explain why tactile maps and diagrams must not present too many elements. However, the exploration can be facilitated by carefully designing the map or diagram so as to fully take advantage of users' abilities to identify symbols, the orientation of lines and textures. Another way to facilitate the exploration is to use efficient strategies: tactile graphics are perfectly adapted to multiple hand/finger exploration, which can prove highly beneficial to retrieve and encode information.

5.2 BENEFITS OF MULTIPLE POINTS OF CONTACT

Tactile maps and diagrams are inherently physical, i.e. they are real 2D objects, unlike online maps for example. Because of this *physicality* they can be scanned with two hands simultaneously and each part of the hand, be it the fingertips or the palms, can be in contact with the tactile document and can be used to retrieve a piece of information [144,219]. In other words, tactile graphics provide multiple *points of contact* [219]. Although such a feature may not appear essential, multiple hand/finger exploration is quite "natural" and can actually lead to efficient strategies for retrieving and encoding spatial information. In Part C, we will see that some interactive maps and diagrams (e.g. maps displayed on touchscreens) do not support multiple *points of contact*, which may be an issue.

5.2.1 SPONTANEOUS USE OF MULTIPLE HANDS/FINGERS

Lederman and Klatzky observed visually impaired users' spontaneous hand movement when exploring a 3D object [160]. From these observations they identified six "exploratory procedures" that can help users extract information. Tactile graphics support three of them [219], therefore taking advantage of visually impaired users' spontaneous strategies: *lateral motion* enables users to identify textures by moving the fingers back and forth across a texture or a feature; *contour following* enables users to detect edges; *whole-hand exploration of global shape*, also referred to as *enclosure*, enables users to identify global shapes by touching "as much of the envelope of the object as possible". In a similar study where blindfolded participants were asked to identify 3D objects, Klatzky et al. [145] also observed that preventing users from freely moving their hand led to inferior performances (as compared to unconstrained movements): therefore, kinesthetic information is also essential when exploring a 3D object and is probably also beneficial during the exploration of tactile graphics.

In a study by Wijntjes et al. [340] blindfolded participants were asked to identify raised-line drawings. Results show that most of the time, participants used two hands, rather than a single hand. When using two hands, two strategies were observed: participants either used one hand as an anchor point while the other scanned the drawing or they used both hands simultaneously. The authors indicate that this latter strategy facilitates symmetry detection. Although the participants were sighted, similar results may be expected for blind participants.

Concerning the number of fingers, Heller et al. [98] asked participants to use one finger only to explore a haptic ruler, and reported that "many [participants] said that this exploration method was not natural, and one person stated that he thought that it was like asking a sighted person to view the world with one eye". Even though such strategies may be a consequence of teaching or training, it suggests that blind users are more likely to use several fingers than one.

5.2.2 STRATEGIES TO RETRIEVE INFORMATION

In addition to being relatively natural, two-handed exploration allows one to efficiently retrieve pieces of information compared to exploration based on a single finger/hand. In the experiment by Klatzky et al. [145] participants were also asked to identify raised-line drawings of the objects using one or five fingers. Results concerning the identification of raised-line drawings revealed that performance (reaction times and percentage of correct answers) was better when participants used five fingers instead of one. Morash et al. [211] found similar results with visually impaired participants. Fourteen blind subjects had to perform different tasks by exploring tactile maps in the following conditions: using between one and five fingers of the dominant hand, using the two index fingers, using ten fingers. Results showed that participants performed the task faster when using two hands and several fingers, for example to determine the number of paths in the map, to relocate a landmark or to compare distances. For tasks requiring straight-line movements (e.g. to find which landmark is directly to the left of another) and distance comparison tasks, each additional finger provided a small extra benefit.

As we said in Chapter 2, Part B, 5, particular strategies of exploration can also be developed to quickly gain an overview of a tactile map or diagram. In fact, visually impaired users are taught to first use both hands in order to scan the map, starting from the upper left corner and moving towards the bottom right corner. This allows them to identify global features such as the number of different textures, the general distribution of the elements of the document or its size [195,219,332]. In their analysis on the use of tactile bar charts by four visually impaired students, Wall and Brewster [328] observed that participants systematically use this strategy: "the first action that all the participants took, even before questions were posed, was to feel over the graph with both hands to obtain a rapid overview of the information available on the page. This included gaining a rough idea of how many bars were in the chart, where particularly high bars were located, and any particularly low bars. Also the participants checked for resources, such as legends, axes and labels". It is only after such an action that participants use their fingers to access details.

Wall and Brewster [328] also noticed that participants used both hands to quickly find a particular value or to compare the height of two bars. Millar and Al-Attar [202] also showed that using two hands could help participants to better estimate distances on a tactile map: one finger is used to follow the line whose distance must be estimated while the other hand concurrently scans the frame surrounding the map. During tests that we conducted, we also observed that participants used their hands or fingers to compute distances, by counting how many hands/fingers could "fit" between two landmarks.

5.2.3 STRATEGIES TO ENCODE INFORMATION

The main advantage of using two hands or several fingers is that it allows the encoding of information using an external frame of reference and/or to relate elements to each other spatially, leading to allocentric rather than egocentric representations. For example, in a study by Millar et al. [203] participants were asked to recall the positions of five landmarks displayed on a raised-line map. In one condition, users were told to use one hand to locate the landmarks and the other to scan the frame surrounding the map. In the baseline condition, no instructions were given. Participants performed better when they were told to use one hand to locate the landmarks, i.e. when they were using an external frame of reference.

Using two hands or several fingers blind users can quickly scan the map to easily locate elements. This enables "back-and-forth" exploratory procedures that have proved to be beneficial in terms of spatial encoding. In a study by Ungar et al. [315] blind children were asked to explore and reproduce a layout of shapes. Children were either seated at the same place or they were seated at a new position that required them to reproduce the layout of the shapes with a rotation of 90°. They observed that children who memorized the shapes in relation to each other and to the frame of the display performed better than the children who explored the objects one after the other. With this latter strategy, children probably encoded the layout of the shapes with respect to their body or arm movements, leading to an *egocentric* representation instead of an *allocentric* representation. Similarly, Gaunet et al. [74] observed that « back-and-forth » exploration strategies led to better performances for tasks requiring mental rotations, as compared to "cyclic" exploration where elements are explored one after the other, i.e. without using an external frame of reference.

5.3 IMPLICATIONS FOR THE DESIGN OF INTERACTIVE MAPS AND DIAGRAMS

Several implications for the design of interactive maps and diagrams can be drawn from the above-mentioned studies and characteristics of the sense of touch. Firstly, because of the spatial resolution of the sense of touch, a limited amount of information can be conveyed: for example, it is not possible to superpose different patterns and labels, as is possible with visual graphics. Secondly, as the haptic system is efficient at identifying symbols, the orientation of lines and textures, interactive maps and diagrams should as much as possible take advantage of these perceptual characteristics. Thirdly, one should keep in mind that any exploration relying on the sense of touch can be quite challenging as it implies a mental integration of information over time and space, which is a process that is cognitively demanding. Such a cognitive workload can be further exacerbated if the technology used does not support multiple points of contact. Finally, we highlighted several ways multiple hand/finger exploration could be beneficial: in addition to being a spontaneous way to explore 3D and 2D objects, such an exploration support effective strategies for retrieving and encoding pieces of information. For example, we showed that it allows users to easily gain an overview of the graphic, to compute distances and to compare elements that do not pertain to the same cluster of elements. Also, visually impaired users must rely on their memory to relate the part of the graphic that they are currently exploring to the parts previously explored. However, if the graphic supports two-handed exploration, users can quickly relocate the other parts of the graph and compare their location so as to better understand how the different parts of the graphs are related to each other. We also highlighted the fact that using both hands enabled users to develop effective strategies to encode spatial information, for example by using one hand to explore the map or diagram and the other to scan the frame surrounding it. Such strategies may result in *allocentric* rather than *egocentric* mental representations and are therefore highly beneficial. Therefore, interactive maps and diagrams should as much as possible support exploration strategies based on multiple points of contact.

6 CONCLUSION OF PART B

In this section we described the current practices for the production and construction of tactile maps and diagrams. We discussed the main characteristics of static maps and diagrams, which can be produced using a variety of methods including embossing, thermoforming, microcapsule paper, 3D-printing and inkjet technology, as well as those of updatable maps and diagrams that can be constructed using magnetic, cork or self-adhesive boards. We discussed the fact that even if static maps and diagrams can be used to present relatively complex information, they are not updatable and are limited by the use of Braille labels. On the other hand, updatable graphics are not constrained by Braille labels but are mainly used to construct simple representations that cannot be stored. Overall, neither static nor updatable graphics can be independently accessed: they either need to be produced by a tactile graphics specialist or to be constructed with the help of a sighted person. We therefore highlighted two ways maps and diagrams could be improved: automating their production is a hard but not impossible task and will certainly be more and more common with the increasing development of computer vision algorithms and/or open source data (such as OSM maps). Another way is to make them interactive: in this way, Braille labels become unnecessary as they can be replaced by audio labels, and users can be guided to produce or construct and then save their own updatable maps and diagrams, making the presence of a sighted person also unnecessary. Interactive maps and diagrams, however, should be designed so as to take full advantage of the tactile abilities of the users while taking into account the limitations inherent to tactile perception. In the last section, we specifically discussed why interactive maps and diagrams should as much as possible support an exploration based on multiple points of contact.

PART C

INTERACTIVE MAPS AND DIAGRAMS FOR VISUALLY IMPAIRED USERS

1 INTRODUCTION

There is an extensive literature on interactive maps and diagrams for visually impaired users, most of which deal with the design, implementation and evaluation of innovative prototypes. To present them, we rely on and extend a classification that we published in a book chapter in collaboration with Anke Brock [50]. Although several classifications had been proposed, none covered all types of prototypes and they all relied on various terminologies. This book chapter was an attempt to structure the work that had been conducted on accessible interactive maps. It provided an exhaustive list of interactive maps prototypes, from the earliest, proposed by Parkes in 1988 [230], to prototypes designed in 2016. It was based on Anke Brock's thesis dissertation [23] but covered a larger design space, included more recent prototypes and, as we said, resulted in a new classification.

In this part we propose to further extend this classification by taking into account prototypes of interactive *diagrams*. Instead of providing an exhaustive list of maps and diagrams, we present within each subcategory a number of illustrative examples. In particular, we focus on prototypes that were evaluated (or at least tested) with visually impaired users in terms of usability (how well could the users interact with the system) and understanding (to what extent users could understand the map or diagram). Throughout this chapter, the expression "**interactive maps and diagrams**" refers to any type of prototype that enables visually impaired users to access maps or diagrams in an interactive manner.

2 CLASSIFICATION OF INTERACTIVE MAPS AND DIAGRAMS

2.1 EXISTING CLASSIFICATIONS AND TERMINOLOGIES

A number of classifications and terms have been used to review existing prototypes of interactive maps and diagrams. For instance, Zeng and Weber [349] classified interactive maps in four groups: 1) "virtual acoustic maps" are entirely based on verbal and non-verbal audio output (for instance, the user interacts by tapping on a tablet which then produces audio feedback); 2) "virtual tactile maps" make use of haptic devices (e.g. a force feedback joystick or mouse); 3) "braille tactile maps" are based on the use of dedicated raised-pin displays (similar to Braille tablets); 4) "augmented paper-based tactile maps" use a raised-line map as an overlay over a touch-enabled display combined with audio output.

Brock [23] classified interactive map prototypes that were designed before 2012 in terms of input and output modalities and according to the type of devices used. The prototypes were either unimodal or multimodal, and the input and output modalities included touch and audio (verbal or non-verbal). The types of devices included haptic devices (joystick, gamepad, mouse, and 3D haptic devices); tactile actuators (displays with dynamic pins, augmented mouse and latero-tactile[23] displays); touch-based devices (touchscreens, tablets, smartphones, tables); and miscellaneous devices such as keyboards, tangible objects and devices based on body-rotation or image recognition.

O'Modhrain et al. [219] focused on refreshable displays, i.e. displays whose content can be dynamically updated, and identified six categories: 1) "surface haptic displays" refers to displays that can modulate the friction between the surface and the fingertip, creating a sensation of relief; 2) lateral skin displacement displays apply lateral forces to the fingers; 3) vibrotactile displays mainly refer to digital graphics that are displayed on a touchscreen that vibrates when the user passes over an element; 4) tactile shape displays are equivalent to raised-pin displays; 5) bubble displays refer to an emerging technology for shape-changing interfaces with inflatable elements; 6) force displays are equivalent to haptic soundscapes and are also referred to as (virtual) haptic displays.

Overall, apart from the one proposed by Brock [23], existing classifications did not embrace all types of interactive map prototypes. For example, Zeng and Weber [349] did not include tangible maps and O'Modhrain et al.'s classification [219] did not include static displays. In addition, one drawback of classifying interactive prototypes based solely on their technology is that prototypes that support very different strategies of exploration are grouped together. For example, although prototypes that rely on a mouse augmented with two Braille cells support a very sequential exploration, they are classified in the same category as raised-pin displays, which support two-handed exploration. Besides, except in [349], we did not observe any attempt to more precisely define a terminology to refer to the different types of interactive maps. Various names have been chosen in different publications, depending on the proposed classifications. The classification that we proposed in [50] covered a larger design space than in previous work (including, for example, tangible maps) and grouped together maps that share similar characteristics in terms of exploration. Finally, these classifications either concerned interactive maps or interactive diagrams, although the approaches that have been proposed to design interactive maps or interactive diagrams are similar.

2.2 PROPOSED CLASSIFICATION

In this thesis, we extend the classification of interactive maps that we proposed in [50] to interactive diagrams. In fact, we observed that very similar approaches have been used for maps and diagrams. Despite the fact that they may serve different goals, similar design challenges must be addressed, be it in terms of exploration, content, affordability or updatability.

In this classification, we distinguish between *digital* maps and diagrams whose representations are purely digital (i.e. none of the elements of the maps or diagrams is embedded into a physical object) and *hybrid* maps and diagrams whose representations are both digital and physical. This classification does not include maps and diagrams that are purely physical, i.e. that do not make use of any interactive technology (such as static tactile ones). We first present *digital* prototypes

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[23] As we will see later in this part, latero-tactile displays deform the skin of the fingertip with an array of laterally moving pins actuated by motors.

according to the input device used for exploration: regular pointing devices, pointing devices with additional somatosensory feedback or finger. We then present *hybrid* prototypes according to the physical representation they rely on (as they can all be explored using both hands): interactive tactile maps and diagrams, tangible maps and diagrams, and refreshable tactile maps and diagrams.

3 DIGITAL MAPS AND DIAGRAMS

Digital maps and diagrams can be displayed on a screen or projected onto a flat surface. They can be explored with one or many points of contact, which are either direct (e.g. fingertips) or indirect (e.g. the cursor of a mouse). Most of the regular input devices, such as keyboards or joysticks, only provide auditory feedback. Other input devices can provide additional somatosensory feedback (e.g. a mouse with braille cells or a force-feedback joystick).

3.1 REGULAR 2D-POINTING DEVICES

3.1.1 KEYBOARD

Keyboards are standard and inexpensive input devices that are widely used by visually impaired users. They can easily be used to move the cursor from one country to another on a map or from one data point to another on a graph. Although they have rarely been used for the exploration of maps, a large number of keyboard-based diagrams can be found. Nevertheless, in many digital map and diagram prototypes, keyboards were used for additional functions (i.e. command selection) rather than for spatial exploration or navigation.

iSonic [352] was a tool for the exploration of thematic maps[24]. The map was divided into a 3x3 grid and each cell was mapped to one key of the numerical keypad. By pressing one of the nine keys, users could retrieve data associated with the corresponding region. The arrow keys also enabled users to navigate within the map. The keyboard was also used for zooming. The authors conducted a user study which showed that most of the participants used the 3x3 keys to navigate the map, while the arrow keys were used to answer specific questions such as finding the adjacent regions. Some participants managed to understand the overall layout of the map using the 3x3 navigation keys. Delogu et al. [45] proposed a similar prototype for the exploration of thematic maps. Participants were able to build an effective cognitive map; however, they did not explore as many regions as users who could navigate the maps with a tablet instead of a keyboard. Delogu et al. [45] concluded that the absence of a reliable reference frame and the step by step displacement when using the keyboard demanded a greater cognitive effort for integrating the map configuration.

iGraph-LITE [63] provided visually impaired users with an access to line charts by generating verbal descriptions of the graph or of parts of the graph. Users could navigate the graph or retrieve particular pieces of information using a set of commands, each command corresponding to a key. Two evaluations were conducted with blind participants who had to answer a number of questions concerning line graphs composed of three, six or seven data points. An initial

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[24] Although we describe all prototypes using the past tense, some of them may still be in use or under development.

evaluation showed that participants were able to answer the questions correctly (around 90% of correct answers) and found the system easy to use, but they did not use optimal strategies to navigate the graph. SoundVis [27] used a similar technique for navigation (the left and right arrow keys allowed users to move one step left or right along the x-axis). However, it enabled visually impaired users to access line graphs composed of two data series (instead of one) and relied on *sonification* instead of verbal descriptions. The principle of sonification is to associate a non-speech sound to each point represented in the graph. The y-value is usually encoded by the pitch of the sound while the x-value is encoded by a note [183]. Keyboards were also used for the exploration of diagrams that are hierarchically organized, such as UML Class Diagrams [198] or molecular structures [26]. The evaluation of this later prototype, called Kekulé, showed that one of the greatest difficulties encountered by the participants was to keep track of their position or "to return to a previously visited atom".

3.1.2 JOYSTICK

Picinali et al. [237] implemented a device that used a regular joystick for navigating a virtual environment. The virtual environment represented a corridor leading to a few rooms and provided 3D sounds (music, voices, etc.). Footstep noises were played every 50 cm, and finger snapping noises could be triggered by the user at any time to determine the position of objects by listening to the echoes. The navigation speed depended on the pressure applied to the joystick. Results of the user study showed that participants were able to build correct mental representations of the environment, and that these mental representations were similar to those acquired through actual navigation in the real environment. To our knowledge, regular joysticks have not been used to make interactive diagrams accessible to visually impaired users.

3.1.3 TANGIBLE POINTING DEVICES

In this subcategory we refer to the use of objects to move a cursor over a map or diagram. We do not refer to maps and diagrams whose representations are embedded into several tangible objects. In the specific context of this classification, we consider the computer mouse as a tangible pointing device.

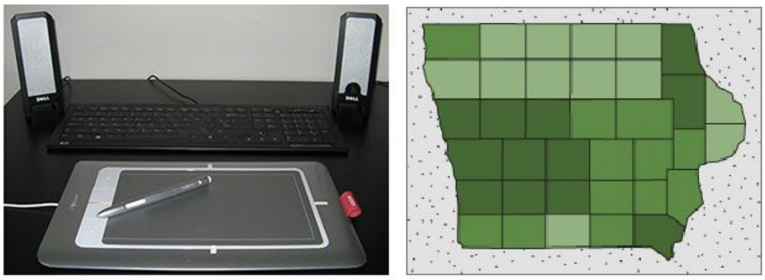

Figure 2.10. The prototype of Brittell et al. [22]. **It used a pen-based digitizer tablet to explore a map showing population density (left). Different sounds were played depending on the color of the area under the stylus (right). Retrieved from** [22].

Earth+[25] was a project developed by NASA where the user moved the mouse within the map. The visual image was transcribed into auditory feedback, with different colors corresponding to different notes. These notes were then played according to the current cursor position. Brittell et al. [22] used a pen-based digitizer tablet with a stylus to present a choropleth map to visually impaired users (Figure 2.10). Depending on the position of the stylus, different queries were sent to a spatial database to provide the user with up-to-date content. Different sounds were played to inform the users about the population density as well as to indicate when they were near a border or outside of the map. A reference grid was implemented to help users navigate the map, but did not prove particularly relevant; participants either ignored it or were distracted by it. Additional feedbacks were also tested to help users follow lines, but this did not result in improvements either: participants "developed a zig-zag gesture" that "introduced additional movements". Finally, the authors reported that participants had difficulty in understanding the layout and shapes of some polygons.

With the GUESS system [131], users could interact with a tablet using a stylus as an input device in order to explore figures composed of simple geometrical shapes (circles, triangles, etc.). Two types of feedback were given and indicated either the type of shape (using a sound that "moved" in a 2D space, i.e. a spatialized sound) or the position of the shape with respect to the whole figure. Different techniques were implemented to facilitate exploration: the technique based on a 3x3 grid was the fastest (different sounds were played whenever the stylus switched from one cell to another, with a distinct sound for the center cell). Some participants reported that the grid facilitated navigation and found the specific sound associated with the center cell particularly useful as a point of reference. The PLUMB system [37], which enabled the exploration and creation of graphs composed of nodes and edges, also relied on the use of a stylus. Sounds were played whenever the stylus touched a node or an edge. However, the authors reported that participants had difficulty in finding a specific node, to handle the stylus and to follow edges.

3.2 POINTING DEVICES WITH ADDITIONAL SOMATOSENSORY FEEDBACK

Visually impaired people are used to both auditory and tactile cues. The abovementioned prototypes provided auditory feedback only, which may limit their ability to convey information. Many digital map and diagram prototypes have used pointing devices with additional force or cutaneous feedback.

3.2.1 FORCE FEEDBACK

Force feedback devices embed motors or actuators that mechanically produce a force that users can perceive as if they were actually touching a surface. For example, when trying to cross a virtual wall, users would experience a sensation of resistance coming from the device. Force feedback devices can have different degrees of freedom and include computer mice, gamepads, joysticks and devices with handles (Figure 2.11).

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[25] http://prime.jsc.nasa.gov/earthplus/ [last accessed September 29th 2016]

Figure 2.11. Three force-feedback input devices. Left: the Logitech Wingman mouse. Middle: the Microsoft Sidewinder joystick. Right: a Sensable Phantom device (now redistributed by Geomagic).

MICE

Force feedback mice provide additional tactile feedback that may be helpful (e.g. [30]). With the map prototype proposed by Rice et al. [253], audio feedback was provided depending on the mouse's position (e.g. the name of a country was given when the mouse entered this country) but a haptic grid overlay and a haptic frame were also rendered by the mouse. Moving the mouse over the grid produced force feedback and allowed users to keep a sense of distance, scale, and direction. The haptic frame around the map served as a barrier to present the map outline. Rice et al. [253] reported that the frame was helpful for the users. However, Lawrence et al. [157] observed that users encountered problems regarding spatial orientation with such a device, even if a grid was provided.

Yu et al.'s web-based tool [347] enabled visually impaired users to explore and create line graphs, bar charts or pie charts using a force feedback mouse (see Figure 2.11, left). Users could navigate a virtual grid and add data points using a keyboard or a mouse. The feedback provided by the mouse helped them to locate the position of the cursor in the grid. Users could thereafter explore the graph: moving the mouse over a line, a bar or a pie section triggered particular *enclosure* effects so as to "trap" the cursor inside the shape. An evaluation showed that the combination of audio and haptics feedback led to a better performance than audio or haptics only. The authors also suggested that the interface should be full-screen "so that the mouse cursor will not move out of the interface. Otherwise, users lose track of the cursor position and get confused".

GAMEPADS AND JOYSTICKS

Other prototypes used gamepads (e.g. [229]) or joysticks (e.g. [154]) with force feedback (see Figure 2.11, middle). Both are affordable and available as mainstream products. In the BATS prototype [229] the input device provided slight or large bumps when the cursor moved across boundaries as well as vibrations when the cursor moved over a city. Schmitz and Ertl [269] used the vibrations of the gamepad to indicate when the cursor was in the proximity of a street. Users could navigate the map by moving the analog sticks of the gamepad.

The TeDUB system [67] transcribed images or text-based representations of diagrams (electronic circuits, UML diagrams and architectural floor plans) into accessible and hierarchical representations that the user could navigate using a keyboard or a force feedback joystick (which could indicate directions). Verbal descriptions of the whole diagram or of the elements of the diagram were given, as well as spatialized sounds.

HANDLES

Other haptic devices rely on a handle that can be moved and eventually rotated in space and that allows interaction in three dimensions (see Figure 2.11, right). The user that grasps the handle (usually a stylus) can sense the force that is produced by the device. This type of device has been widely used for the exploration and creation of maps and charts.

The prototype by De Felice et al. [62] allowed the exploration of indoor environments as well as complex geographical areas. Each element of the map (doors or rivers for example) was associated with a specific haptic feedback. Users could select the content that they wanted to display as well as change the scale and level of details on the map. Interestingly, SeaTouch [283] allowed blind sailors to prepare a journey by exploring a map which provided haptic feedback (via the commercially available Phantom device), text-to-speech output and ambient sounds.

Yu et al. [346] developed a system also based on a Sensable Phantom haptic device (see Figure 2.11, right) for the exploration of line graphs and bar charts (bars were "engraved"). When compared to a traditional tactile diagram the haptic prototypes resulted in better accuracy scores but also in larger completion times and a higher cognitive workload. In a later study, McGookin and Brewster [193] proposed to use multiple views to facilitate the exploration of graphs (SoundBar system). In addition to a standard exploration of the graph, an overview of the graph was provided using non-speech sounds: when navigating along the x-axis, notes were played according to the height of each bar. An evaluation conducted with blindfolded participants showed that participants gave more correct answers and took less time to complete the task using the SoundBar system. Users were able to quickly identify bars in order to find the maximum value.

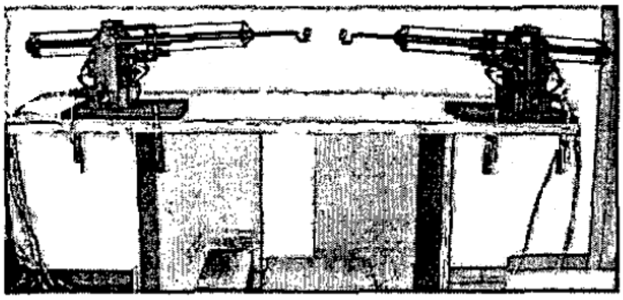

Figure 2.12. The "GRAB" interface was composed of two handles. After [110]**.**

Iglesias et al. [110] worked with the "GRAB" interface (Figure 2.12). This device also created 3D force feedback but in contrast to the previously mentioned devices it had two distinct handles. Two fingers, either from the same or different hands, were placed in two thimbles onto which two independent forces were applied. Several applications were developed, including a chart data explorer (line graphs, bar and pie charts) and a city-map explorer. Observations confirmed that using a second finger "can be vital as an 'anchor' or reference point that allows [users] to orientate themselves in space, more readily understand objects' relationships (distribution and distances) and makes re-finding objects easier".

3.2.2 CUTANEOUS FEEDBACK

Input devices can also be augmented with cutaneous feedback. The more common devices include mice with an array of pins, in which the pins move up and down according to the cursor location. For instance, the VTPlayer by VirTouch was such a tactile mouse with two 4x4 matrices of pins (Figure 2.13, left). The pins are located under the index and middle fingers, and are raised up or down according to the cursor location.

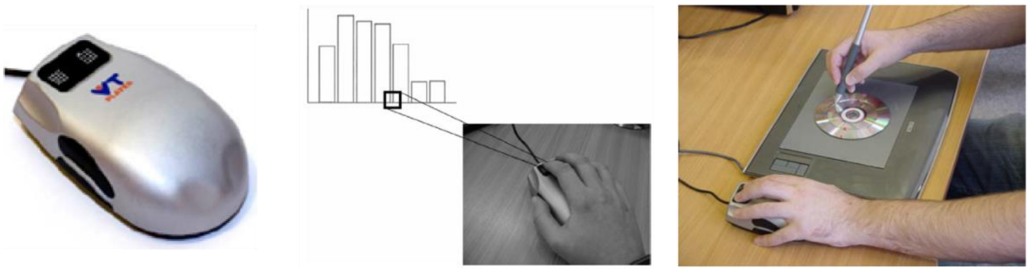

Figure 2.13. The VTPlayer Mouse. Left: The VTPlayer mouse is composed of two Braille cells. Middle: Exploration of a bar chart with a VTPlayer mouse (retrieved from [326]**). Right: With the Tac-tiles system** [327]**, the non-dominant hand of the users rested upon the mouse while the other hand was used to move a stylus above a tablet (retrieved from** [327]**).**

Using such a device, Jansson et al. [122] investigated the readability of several textures to enable visually impaired users to explore choropleth maps (colors being matched to textures). Results of an evaluation conducted with 60 blindfolded participants. They reported several issues with the use of a mouse while without vision: moving the mouse horizontally without rotating the mouse was difficult; the scale difference between mouse movements and cursor movements was difficult to apprehend; the mouse could be lifted and users were not aware of the new position of the cursor.

Wall and Brewster [326] also observed issues with the use of the VTPlayer mouse for the exploration of bar charts (Figure 2.13, middle). Some participants were confused by the similarity of the output of the mouse with Braille cells and expressed concerns with the size of the display and its low resolution. In addition, the "lack of constraints and guidance proved to be a significant problem for all users". To address these issues, a new prototype was designed: the non-dominant hand of the users rested upon the mouse while the other hand was used to move a stylus above a tablet. In that way, the tablet could serve as an external frame of reference and the x and y axes were made physical. This set-up received positive feedback and was adapted to enable the exploration of pie-charts with the Tac-tiles system [327] (Figure 2.13, right). As for Pietrzak et al. [239], they used the VTPlayer mouse to give directional cues that guided the users during the exploration of geometrical shapes.

Another type of device is latero-tactile displays: they deform the skin of the fingertip with an array of laterally moving pins actuated by miniature motors. In a study by Petit et al. [233] a latero-tactile device was used to explore a map with two levels of information: one for the continents and the other for the location of five civilizations. Users could switch between these two levels by pressing a key. In this study, the device was mounted on the Pantograph [31], a haptic device that allows 2D-movement over a limited surface (as in Figure 2.14, left). Levesque et al. [165] showed that simple and small shapes could be rendered using the STRESS latero-tactile display (Figure 2.14) and three primitive drawings (dots, vibration and gratings). Shapes filled a 2-3 cm square and included a square, a circle, two triangles, a diamond and a cross.

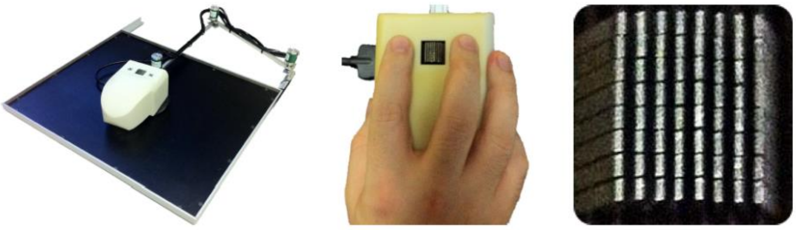

Figure 2.14. The STRESS latero tactile display was composed of an array of 64 actuators. (Retrieved from [165]**.)**

3.3 FINGER-BASED EXPLORATION

Finger-based exploration has been used in many research projects. In this case the input device is one of the user's fingers, onto which the position of the cursor is directly mapped. Feedback can be auditory or tactile (vibrations). The location of the user's fingers can be tracked using a touch-enabled device (e.g. digitizer tablets, smartphones, tablet or tabletops) or a camera.

3.3.1 FINGER TRACKING ON TOUCH-ENABLED DEVICES

Because smartphones, tablets and digitizer tablets are mainstream devices, many accessible map and diagrams projects have used this kind of devices. Moreover, smartphones and tablets have the advantage of being usable in mobile situations. With the term touch-enabled devices, we refer to all devices that directly sense the user's touch inputs.

Figure 2.15. Two prototypes of digital maps with finger-based exploration. Left: TouchOverMap [241] **allowed user to explore maps using vibrational and vocal feedback (retrieved from** [241]**). Right: in** [79]**, vibrations and sounds indicated whether the user was touching vertices or edges (retrieved from** [79]**).**

Jacobson's prototype [117] allowed visually impaired people to explore auditory maps by pressing specific areas on a touchpad (north, west, south, east, and zoom buttons). Verbal descriptions, ambient sounds (such as traffic noise) and auditory icons were played during exploration. Five visually impaired and five blind people evaluated this device. All of them were able to use it and found it "simple, satisfying and fun". TouchOverMap [241] provided a basic overview of a street map displayed on a smartphone, by giving vibrational and vocal feedback when the finger passed over a map element (e.g. streets or buildings, see Figure 2.15, left). The evaluation, performed with eight blindfolded sighted users, showed that all participants acquired a basic understanding of the "zoomed-out" and "zoomed-in" version of a map, even though they found the "zoomed-out" condition difficult. The authors indicated that this was probably due to the fact that in the zoomed-out condition there were too many elements, which made them hard to distinguish. In particular, the authors observed that it was impossible to know if "roads were close or if they crossed" and that "it [was] hard to tell the directions of short roads".

AudioFunctions [294] combined sonification techniques with gestural interaction to enable a visually impaired user to follow a mathematical function displayed on a touchscreen. Users answered as many, or more, correct answers using the prototype than when using raised-line diagrams only, but they also took significantly longer (about nine minutes with the prototype vs five minutes with the tactile graphs). Giudice et al. [79] combined gestural input with audio and vibrational feedback (Figure 2.15, right). As the users moved their finger over the tablet, vibrations indicated whether they were touching edges or vertices. This prototype proved efficient for the exploration and understanding of bar charts (composed of four bars) as well as for letter recognition tasks and orientation discrimination tasks, but following contours and staying well orientated remained challenging in the tablet condition, as compared to the tactile condition. In a similar study, Klatzky et al. [144] asked 18 blindfolded participants to explore either zigzag lines composed of four or five inflexion points or line graphs composed of two data series (five data points each), in order to answer questions such as identifying the minimum y-axis value or the line with the steepest slope. Regardless of the conditions (vibratory only, auditory only or bimodal), participants spent more than half of the total time off the target lines and completion times were relatively high (around 4 minutes on each figure). Nevertheless, participants were able to answer the questions and to correctly sketch the figures.

Interestingly, the GraVVITTAS prototype [83] also combined a tablet with audio feedback, but external vibrating motors were attached to the right and left index fingers of the user, thus providing two points of contact (Figure 2.16). In addition, two interaction techniques were designed to facilitate the exploration, which the users could activate on demand: 1) 3D sound indicated the position of the shapes displayed within a certain distance of the finger (e.g. if a shape was located to the right of the finger, audio was played as if it was coming from the right of the user); 2) a sound was played for every element displayed between the two fingers of the users (*scanline* technique). Six visually impaired participants, who had already used the prototype for at least four hours, were asked to explore a table (four rows and four columns), a floor plan and a line graph with two data series (seven data points each) in order to answer several questions (see Figure 2.16, right). Results were in line with previously mentioned studies: users managed to correctly answer the questions but completion times were relatively high; participants took almost four minutes to find a particular value on the line graph and around three minutes to identify the slope of one of the two lines.

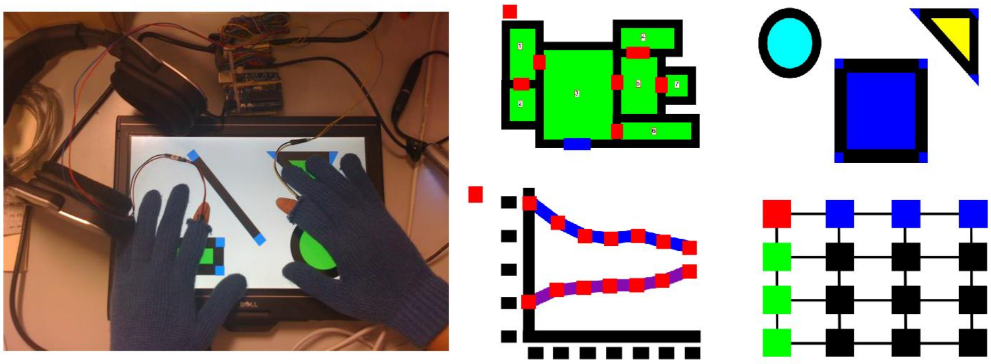

Figure 2.16. The GraVVITAS prototype [83]**. The prototype enabled visually impaired users to explore various graphical representations (right) and provided two points of contact (the user's index fingers). Retrieved from** [83]**.**

3.3.2 CAMERA-BASED FINGER TRACKING

Cameras (including webcams, embedded smartphone cameras, stereo cameras or motion-capture systems) can be used to detect one or many user's finger(s). In contrast to touch-enabled devices, it is possible to identify each finger.

AccessLens [132] enabled visually impaired users to interact with paper documents including elements with labels. The camera placed above the table was used to decode the labels and recognize the user's gestures. Users could retrieve the names of the elements, and they could also use a gesture or voice command menu. During the evaluation, five blind users were asked to explore a diagram, a map of the USA, or a table presenting poll results. Qualitative results showed that the participants were highly satisfied with the system and the interaction modes even if they faced some interaction issues (when placing both hands on the document for example).

Bardot et al. [5] used a motion tracking system to track a smartwatch during map exploration (Figure 2.17). Motion tracking allowed both 2D gestures (for exploration) and mid-air gestures (to filter data). The smartwatch provided sound and vibrational feedback, in addition to different filtering commands. A two-step guidance function based on vibrations helped users find specific targets. In a follow-up study, Bardot et al. [6] used a similar set-up to track one of the user's fingers. The maps were composed of several areas, each area being associated with a name and quantitative data. Three exploration techniques were designed: the Plain exploration technique simply provided auditory feedback when the finger was entering an area; the Filter technique relied on filter selection on the smartwatch and enabled the user to select which data to display; the Grid-Filter technique combined the Filter technique with the use of a virtual 3x3 grid that the user could explore using mid-air gestures. The evaluation, including twelve visually impaired participants, compared the exploration of a regular raised-line map to the exploration of a digital map with these three different techniques. It showed that the exploration of a digital map, without any tactile cues, is possible. It also showed that the Grid-Filter technique is efficient for data selection or comparison tasks.

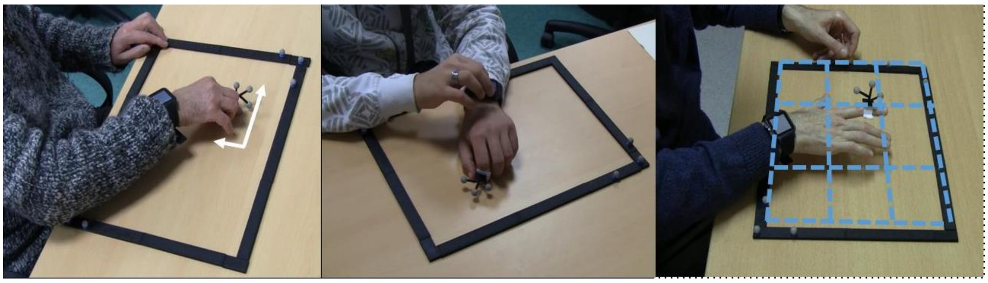

Figure 2.17. In the prototype of Bardot et al. [5]**, a smartwatch vibrated and emitted sounds to enable visually impaired users to explore virtual maps. Three exploration techniques were designed (from left to right): Plain, Filter and Grid-Filter. Retrieved from** [5]**.**

3.4 SUMMARY OF DIGITAL MAPS AND DIAGRAMS

3.4.1 COST AND AVAILABILITY

Digital maps and diagrams' representations do not rely on any physical object, which make them dynamically updatable. However, input devices are required to access the digital content, whose cost and features are worth discussing. Prototypes based on regular devices such as keyboards, mice and joysticks are cheap and widespread but only provide auditory feedback. Tangible input devices such as styluses must be tracked using a camera or a touch-screen device but their cost remains very low and no dedicated hardware is required. The same applies to finger-based devices that either require a touch-enabled device or a camera, except that vibrations can be conveyed, providing additional and helpful feedback. One obvious advantage of using a touchscreen, a tablet or a smartphone is that these devices are widespread, affordable and do not need any calibration process. On the contrary, cameras depend on lighting conditions, are affected by occlusions and shadows and must be calibrated. Motion-capture devices offer enhanced opportunities such as using mid-air gestures, but they are much more expensive and need accurate calibration as well as a fixed setting. Finally, prototypes based on pointing devices with additional somatosensory feedback are very interesting but they require dedicated hardware that is not widespread and not as cheap as tablets for example.

3.4.2 FACTORS IMPACTING EXPLORATION

With very few exceptions, most digital maps and diagrams prototypes provide a single point of contact: this means that participants can only access one piece of information at a given moment and that they cannot develop multiple hand or finger strategies of exploration, as they would usually do with static tactile maps and diagrams. This raises a number of perceptual and cognitive issues.

In most of the prototypes, audio, tactile and/or force feedback is provided whenever the finger or input device touches an element. Therefore, three steps are required to create a global mental image of the map or diagram [144]: 1) users must keep track of the position of their finger or cursor, based on feedback provided by the prototype, if available. Then, 2) they must "interpret the external cue, and [… 3)] associate the cued content with the currently contacted coordinates" [144]. The first step is particularly difficult in the absence of kinesthetic cues or a reliable external frame of reference or of salient points of interest. For example, regular 2D pointing devices such as keyboards and joysticks or force-feedback mice do not provide a frame of reference. Several authors reported that using such devices, participants had difficulties in efficiently navigating the maps or graphs or to keep track of the cursor's position (e.g. [26]). Inefficient strategies of exploration were also observed [63], which may be due to the fact that users could not quickly relocate a point that they had already visited [26].

Touch-enabled devices provide an external frame of reference and users can quickly perceive the spatial extent of the map or diagram, which usually corresponds to the size of the display. However, for such devices, the process of interpreting the external cue (e.g. sound, description or vibration) can be particularly challenging [144]. Empirical studies that we described tend to show that given sufficient time, users are able to explore a map and a diagram and correctly answer questions relative to the overall structure and/or to particular points of interest (data points or landmarks). However, in most cases, exploration was (very) slow and cognitively demanding (e.g. [241]). The main challenge appears to be following lines. In part B, we indicated that the perceptual properties of the haptic system made it possible to easily follow a tactile line. However, on touch-enabled displays, no sufficient information is provided for the user to detect the orientation of the line. A sound or a vibration (that is, furthermore, often not localized, as the whole device vibrates), do not give any clue about the direction of a line. Consequently, users may develop particular strategies (such as the "zig-zag" technique reported in [22]) or inefficient ones (long completion times [83] and much time spent "off the lines" [144]) or, at worst, may not be able to distinguish the orientation of the lines [241]. Following lines with a stylus is also difficult [37].

Unlike keyboards and regular mice and joysticks, force-feedback devices provide an external reference frame because the displacement of the device is generally constrained. The device cannot move over physical limits in space. Rice et al. [253] reported that such a frame was very helpful. The physical limits of the device can be used as a reference frame if they correspond to a static view of the map or diagram. However, if the map or diagram view is displaced when the user pushes towards one side (sometimes called "inertial displacement") the frame of reference may be lost in the absence of efficient feedback. One distinctive advantage of force-feedback devices is that they can "trap" the cursor inside a line or a shape (e.g. [347]), making it easier for the user to follow the contours of the shape and orientate themselves.

Interestingly, several techniques have been developed to compensate for these limitations. A common technique is to provide a grid in order to help users navigate and keep track of the cursor's position, but also to provide them with an overview of what is inside a particular cell. Although the benefits of using a grid have been observed [6,130,254,347], they are not systematic [22,157]. The possibility to quickly have an overview of a map or a diagram was also investigated, be it with a simple button that provided users with an access to a verbal description of the graph (e.g. [83]), or with sonification techniques (e.g. [194,352]). To help users relocate points of interest, different techniques have been proposed such as enabling the users to annotate a drawing [130] or to bookmark points of interest [326]. Also, when using a camera to track the hand instead of a touch-enabled device, tactile cues are missing. To tackle this issue, certain prototypes included a rigid frame that delimited the exploration area (e.g. [6]).

Finally, two projects investigated the use of two points of contact instead of one: the GRAB interface [110] (force feedback device with two handles) and the GraVVITAS interface [83] (two vibrating motors were attached to the users' index fingers). With GRAB [110], the use of a second finger was found very helpful; with GraVVITAS [83], specific findings concerning the use of two fingers were not provided, except the fact that participants used two fingers to determine the slope of a line on a graph and that it was too difficult to distinguish between four vibrating motors (index and middle fingers).

3.4.3 CONTENT

Several prototypes of digital maps and diagrams solely rely on auditory or vibratory feedback. It is therefore possible to render maps and diagrams that are made of several points or separated areas, but the type, number and resolution of rendered elements is obviously limited. Even though 3D sound may increase the quantity and quality of auditory feedback [131], maps and diagrams from this category are generally quite simple and not really expressive. In fact, most of the prototypes of maps based on regular 2D pointing devices were used to display choropleth maps, i.e. maps with regions only [22,45,352] or with a very few number of landmarks [204,238]. Diagrams can be more complex if users can navigate through the hierarchy of a diagram (e.g. [26]) but are usually also limited to the exploration of pie and bar charts, line graphs, geometrical shapes or simple graphs composed of a few nodes and edges. Digital maps and diagrams that are based on less conventional tactile feedback (force-feedback, latero-tactile displays, Braille mice, etc.) can be more complex or detailed. For instance campus maps, alongside buildings plans, country maps with various cities and/or areas, street maps, etc., have been designed. Indeed, a number of cutaneous and haptic feedbacks can be used to render various elements such as boundaries, textures, points of interest, etc. (see [82])

3.4.4 UPDATABILITY

Finally, digital maps and diagrams can be readily updated and are not limited by physical constraints. In that sense, they are similar to visual graphics that sighted users can access online, and share the potential of providing visually impaired users access to a large quantity of data. However, performing zooming and panning operations on digital interactive maps without any tactile cue may lead to sensory and cognitive challenges that have not yet been thoroughly addressed. As for diagrams, a few prototypes supported navigation through several hierarchical levels (e.g. five levels in [198] and three in [130]) but it is unclear to what extent users would manage to keep track of their position with a higher number of levels. Finally, it should be noted that several prototypes enabled the creation, edition or annotation of diagrams, and especially of bar charts (e.g. [195]).

4 HYBRID MAPS AND DIAGRAMS

As we previously mentioned *hybrid maps and diagrams* are made of a digital and a physical representation. There have been many prototypes in the literature relying on different physical displays. We classified them into three categories according to the type of physical display that was used: tactile, tangible or refreshable tactile maps and diagrams.

4.1 INTERACTIVE TACTILE MAPS AND DIAGRAMS

With the term *interactive tactile maps and diagrams* we refer to physical representations that are tactile maps. In contrast with tangible or refreshable maps, which we will introduce below, tactile maps are static. The content cannot be dynamically updated. The only way to alter the map view (zoom or pan for instance) is to change, or erase and redraw the physical representation. In the category of tactile maps, raised-line maps have been extensively used, but more recently 3D-printed maps have emerged. Two different technologies have then been used to track the user's finger(s) over the tactile map: touch-enabled devices or cameras.

4.1.1 INTERACTIVE TACTILE MAPS AND DIAGRAMS WITH FINGER TRACKING ON TOUCH-ENABLED DEVICES

In those maps and diagrams a tactile overlay (e.g. raised-line or 3D-printed) is placed over a touchscreen device that allows the detection of touch inputs through the overlay. Users perform taps or double-taps on any interactive element of the overlay, which produces speech, sound or vibrational feedbacks.

Parkes [230] was the first to design an interactive tactile map with an overlay placed over a touchscreen, even though the technical aspects of his NOMAD prototype were not precisely described. The prototype described by Weir et al. [333] presented weather forecasts of the USA. When the user selected a state by tapping on it, a sound was played whose pitch represented temperature (the higher the pitch, the higher the temperature). Recently, 3D maps have also been used. Taylor et al. [298] developed a web interface that enabled visually impaired users to create and customize their maps (e.g. positions of the labels, textures, etc.) before 3D-printing them. Up to five heights could be rendered and conductive filaments were used, which allowed the user to interact with the map. With LucentMaps [86], users could place a 3D-printed map on top of a touchscreen, which detected the identity of the maps thanks to capacitive markers attached to the sides of the map. The maps were very thin, making it possible for the device to detect the users' touches.

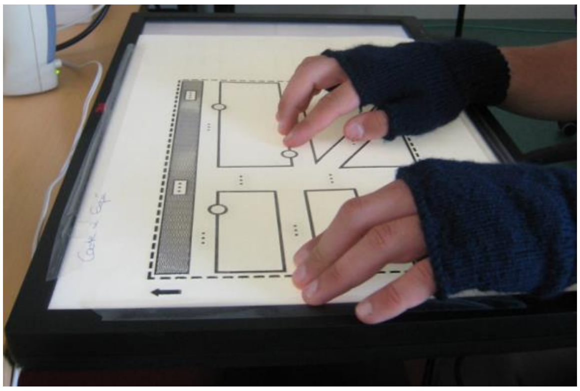

Figure 2.18. The set-up used by Brock et al. [24] **for their evaluation. A tactile overlay was placed over a touch-enabled device. Users could interact with the map by performing taps or double-taps on any interactive element. Retrieved from** [24]**.**

Brock et al. [24] compared the usability of a regular raised-line map to an interactive raised-line map that displayed identical content (Figure 2.18). The evaluation included twenty-four blind participants that were required to explore an unknown neighborhood. The study assessed the time needed for exploration, the accuracy of the spatial learning, and the satisfaction of the users. The results showed that interactivity significantly shortened exploration time and increased user satisfaction. Weir et al. [333] compared the usability of an interactive raised-line map to the usability of a digital map based on a touchscreen or a keyboard. The evaluation showed that the participants preferred the interactive raised-line map over the touchscreen or the keyboard alone.

Although tactile overlays have been widely used for the design of interactive maps, the number of interactive diagrams based on tactile overlays is more limited. An illustrative example is the ViewPlus' IVEO prototype [71], which is currently available on the market[26]. It allows sighted or blind users to create SVG files directly or from scanned images and to annotate them with labels. These labels are then played whenever the user clicks on the corresponding element. The map or diagram must be printed using a Braille embosser and placed on the dedicated device. Another example is Kevin [17], a prototype that translated data flow diagrams into tables. A tactile overlay was used and consisted of a grid: most of the cells represented a cell of the table and the remaining cells were used to provide users with an access to control buttons (e.g. to open or create a new chart).

4.1.2 INTERACTIVE TACTILE MAPS WITH CAMERA-BASED FINGER TRACKING

Another way of tracking the user's fingers is to use a camera. With the Tactile Graphic Helper [69] a visually impaired user could place a tactile graphic on a regular table and then interact with it. The camera, placed above the tactile drawing, recognizes the layout and tracks the user's fingers. The user could point at elements and ask for information. The Tactile Graphic Helper aimed at allowing visually impaired students to discriminate tactile symbols (texture, Braille labels, etc.) without requiring the help of a sighted person. Götzelmann [85,89] designed interactive 3D-printed maps. The production of 3D maps was automatic so that visually impaired users could make them without assistance. Once printed, the fingers were tracked with a smartphone held above the 3D map (Figure 2.19, left). The application identified the map with a printed barcode, and, in addition, helped the user to correctly hold the smartphone over the map. With the other hand, the user was free to explore the map, and received auditory feedback when pointing at elements.

Ramloll and Brewster proposed TouchMelody [247], a system based on a motion tracking system that tracked two sensors mounted on the user's index fingers, therefore providing two points of contact (Figure 2.19, right). Based on two-handed strategies developed by visually impaired users when exploring a tactile map or diagram, spatialized sounds indicated the position of one finger (on the dominant hand) with regard to the position of the other finger (which served as an anchor point). Pitch changed as the vertical distance between the two fingers increased or decreased. Therefore, if the user placed his/her non-dominant finger on the origin of the y-axis, the pitch indicated the y-value associated with the dominant finger. The user could turn off the sound by lifting one finger off the diagram.

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[26] https://viewplus.com/product/iveo-hands-on-learning-system/

Figure 2.19. Two prototypes of interactive tactile maps with camera-based finger tracking. Left: in [85]**, users could interact with a 3D-printed map by holding their phone above it and the integrated camera tracked one of the user's fingers (retrieved from** [85]**). With TouchMelody** [247]**, two fingers were tracked to help users explore bar charts (retrieved from** [247]**).**

4.1.3 ERASABLE TACTILE MAPS AND DIAGRAMS

Recently, an interesting prototype based on 3D-printing was designed by Swaminathan et al. [292]. Linespace was a platform that included a movable 3D printer head mounted over a drafting table (Figure 2.20). The system could print and erase spatial content based on vocal commands and deictic gestures. The gestures were detected by a camera tracking the markers attached to one users' finger. It provided visually impaired users with the possibility to dynamically draw and explore spatial content. Among the different applications described in the paper, one allowed users to search for real estates within a city map. Once the map was printed, the user could retrieve additional information about a particular estate. For rescaling the map or exploring a new part, the system printed a new map on a blank part of the drawing table, which enabled the user to switch back and forth between two different views. The system could also remove elements that have been previously printed by using a "scraper", hence the name "erasable tactile map" that we chose for this sub-category.

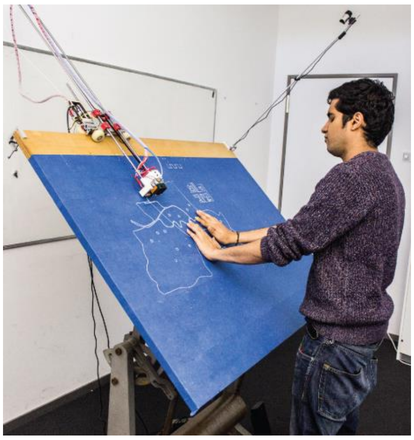

Figure 2.20. Linespace [292]. **The prototype included a movable 3D-printer head. Users could ask the system to 3D-print different parts of the map (similar to panning and zooming). Retrieved from** [292]**.**

4.2 TANGIBLE MAPS AND DIAGRAMS

Tangible user interfaces combine physical objects with digital data, and thus enable interaction with the digital world through the use of physical artefacts [305]. As already mentioned, we make a distinction between digital maps that are based on a tangible pointing device as opposed to tangible maps and diagrams per se. *Tangible maps and diagrams* are made of several physical objects that represent elements and support two-handed exploration. Users can also manipulate the tangible objects in order to (re)construct or edit the map or diagram. On the contrary, tangible pointing devices (such as computer mice, pens or toys) do not represent any element but only serve as a pointing device.

Schneider and Strothotte [272] designed a prototype that enabled visually impaired students to independently construct an itinerary using building blocks of various lengths. The system indicated the length and orientation of the next building block that had to be placed. The user's dominant finger was tracked during exploration of the virtual map, and guided along the route (see Chapter 2, Part E, 4 for a detailed description).

McGookin et al. [196] developed a tangible prototype for the non-visual exploration of graphs. This system combined a fixed grid and movable tangible objects that represent the top of a bar or the turning point of a linear function. By moving a slider along the x-axis, the user could listen to the values of the graphs or linear functions that were sonified (see Chapter 2, Part E, 4 for a detailed description). With the Digitizer Auditory Graph [36], visually impaired users first constructed a simple graph using Wikki Sticks. Then, thanks to a webcam placed above the tabletop and computer vision algorithms, the graph was analyzed and translated into a sonified graph that students could instantly access.

4.3 REFRESHABLE TACTILE MAPS AND DIAGRAMS

Refreshable tactile maps refer to maps that are physically rendered (for example using a matrix of pins), and that the system can dynamically update, for example allowing zooming and panning. Up to now, only one technology has been used: raised-pin displays. This technology relies on pins that are raised mechanically, using a variety of technologies (e.g. electromagnetic, mechanical, …) [263]. Vidal-Verdú and Hafez [322] referred to this type of device as static refreshable displays: they are equivalent to a screen "where pixels are replaced by taxels, i.e. touch stimulation units". An illustrative and well established example is a Braille display, which is used by most visually impaired people to access digital and textual content.

Zeng and Weber [348] used the BrailleDis 9000 tablet, which was composed of 7200 pins arranged in a 60x120 matrix, and actuated by piezo-electric cells (Figure 2.21). Touch sensors allowed the user to provide input to the system (tap or double tap for instance). They designed a set of tactile symbols to display different types of information such as bus stops or buildings. In a second publication [350], they improved the tactile symbol set as well as the prototype, and introduced the ATMap prototype that allowed the users to pan and zoom, but also to share annotations.

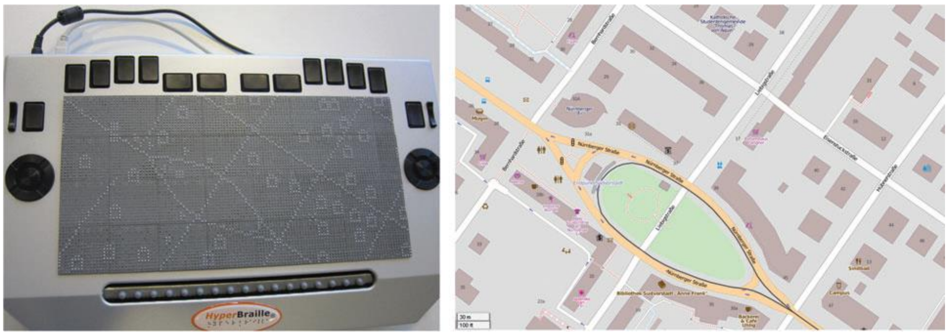

Figure 2.21. The BrailleDis 9000 tablet, composed of 7200 pins, was used in [348] **to give visually impaired users access to dynamic maps. Retrieved from** [348]**.**

As for diagrams, Minagawa et al. [205] used a 8x8 matrix of pins to enable visually impaired users to create and explore diagrams. Each pin could be set to be 0, 2 or 4 mm high, had a diameter of 7 mm and were separated by 10 mm. To draw the diagram, users first needed to select the desired height using a keyboard, and then had to touch the pins they wanted to update. For the exploration, users had to simultaneously touch a pin and press a key in order to retrieve its corresponding label. Shinohara et al. [281] developed a prototype composed of a matrix of 64x64 pins whose height could vary between 0 and 10 mm with 0.1 mm steps, thus enabling the display of "3D shapes". The prototype was used to display familiar objects, maps and scientific diagrams (e.g. an image of the cerebral cortex).

4.4 SUMMARY OF HYBRID MAPS AND DIAGRAMS

4.4.1 COST AND AVAILABILITY

Interactive tactile maps and diagrams do not require dedicated hardware: a touch-enabled device or a camera is enough to make them interactive. However, the main limitation is the production of the tactile overlay that requires dedicated hardware and must be created by a tactile graphic specialist. Despite this limitation, tactile maps and diagrams are now on the market and are being used in many situations at home or at school (e.g. [28]). In the same subcategory, we described interactive tactile maps that can be 3D-printed. They embed conductive markers that are used to identify the map [86] or to enable the user to interact with the map [298]. Such prototypes require a 3D printer, which can be expensive even though such a technology is now relatively widespread. Tangible maps and diagrams can be relatively cheap (a webcam, a PC, and a transparent table suffice). However, existing commercial interactive tabletops that identify and track tangible objects are more expensive (e.g., the Reactable[27]). In terms of availability, a downside of tangible maps and diagrams is that they require a large tabletop and several objects, which may be cumbersome. Finally, most of the Refreshable tactile maps and diagrams rely on raised-pin displays, which are extremely expensive. In 2007, Vidal-Verdu and Hafez [322] estimated that a display large enough to be explored with two hands would require more than 75 000 pins, and would cost approximately 270 000€. In 2012, the HyperBraille display with 60 x 120 pins was worth 50 000€.

4.4.2 FACTORS IMPACTING EXPLORATION

Because they rely on a physical representation, *hybrid* maps and diagrams allow two-handed exploration and support efficient strategies for the exploration of maps and diagrams. In addition, recent interactive tactile maps and diagrams (e.g. [24]) provide many interactive contact points, which support multiple fingers and gesture command menus. Interestingly, Brock et al. [24] observed that visually impaired users prefer not to activate any interactive feedback when they explore a map for the first time. Among existing prototypes of tangible maps and diagrams, only a few supported finger-based exploration and this was limited to a single finger (e.g. [272]). However, it is now possible to track multiple fingers using a camera: therefore not only could tangible maps and diagrams support multiple points of contact, but they could also support multiple points of interaction. As for raised-pin displays, they can also detect touches and therefore offer a wide range of possibilities to interact with the map or the diagram. And despite their low resolution, it is relatively easy to follow lines. Obviously, hybrid maps and diagrams provide a very stable and reliable haptic reference frame. Indeed, any static and physical point of the tactile display (relief, identified item, edge of the display, etc.) can serve as a reference point.

4.4.3 CONTENT

Tactile maps have been criticized for their low resolution when compared to visual maps but they remain the best way for displaying complex content, using different patterns of points (e.g. triangles and circles), lines (e.g. dotted lines and plain lines), and areas (filled and half-filled). When making them interactive, Braille labels can be removed, and new elements can be added [24]. When compared to interactive tactile maps and diagrams, tangible maps and diagrams are more limited by the number and type of elements that they can render. Indeed, tangible objects are generally relatively large, which limits the number of points of interest that can be simultaneously represented. Besides, it is not easy to represent lines; Schneider and Strothotte used physical bricks but their prototype allowed the construction of routes only. Finally, raised-

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[27] http://reactable.com/

pin displays are adapted for rendering various patterns of symbols [350] and lines [115], but their resolution is drastically limited by the size of the device and the number of pins. And even though it is possible to display various points of interest, lines and areas, the current prototypes cannot be used to display complex maps and diagrams. Besides, several pins are needed to distinguish different symbols [350], which requires some space, and hence impacts the map or diagram resolution.

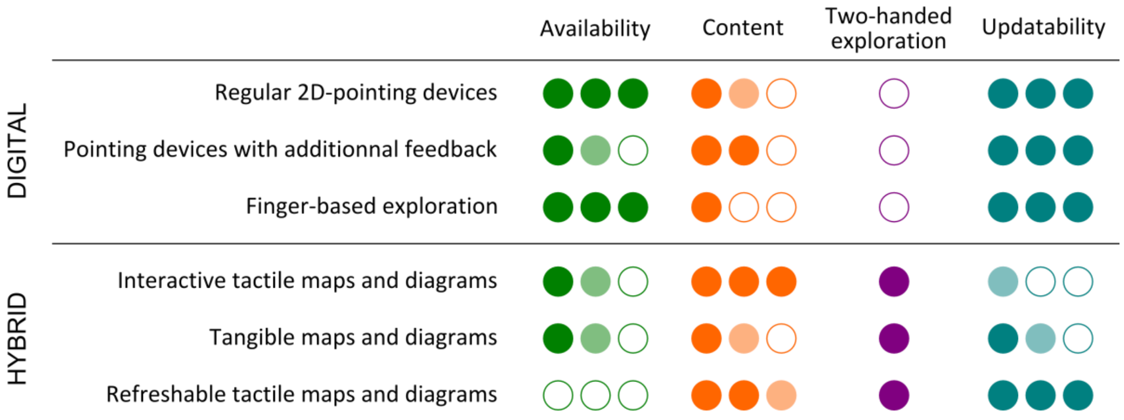
4.4.4 UPDATABILITY

Hybrid maps and diagrams are shaped and constrained by their physical representation. Interactive tactile maps and diagrams are constrained by the tactile overlay, which cannot be dynamically altered. Different map contents, but also different views or different scales, must be rendered with different tactile overlays. Of course, it is possible to pre-print these different overlays, and dynamically load the corresponding digital content when one overlay is being used. However, when panning or zooming, users must interrupt the ongoing exploration in order to replace the overlay, and start a new exploration process after the corresponding digital content has been called. In order to link the mental representations corresponding to both maps, they have to find reference points that are on both overlays. This procedure clearly leads to cognitive challenges. Furthermore, users cannot select a scale or a view that has not been prepared in advance.

Linespace [292], at the intersection between interactive tactile and refreshable tactile maps and diagrams, does not provide regular panning and zooming operations. Instead, a new map with a different view or scale is printed over a blank space around the map currently being explored. However, the cognitive issues that we already mentioned (interruption of the current exploration and finding common reference points) also apply in this case. As for tangible maps and diagrams, because the map representation can be easily manipulated by the user, it is possible to create or edit a map or diagram by adding, moving or removing tangible objects. It is therefore technically possible to rescale or reposition the map or diagram by moving the objects. Obviously, rescaling and repositioning take some time, but it renders the representation more flexible than with interactive tactile maps and diagrams. Refreshable tactile maps and diagrams are the most dynamic interactive displays. It is possible to update the content instantly, but also to provide advanced interactive functions such as zooming and panning operations [280] or annotation [351].

5 SUMMARY

Figure 2.22 is an attempt to summarize the main characteristics of the different approaches that have been used to design interactive maps and diagrams for visually impaired users.



		Availability	Content	Two-handed exploration	Updatability
DIGITAL	Regular 2D-pointing devices	●●●	●◐○	○	●●●
	Pointing devices with additionnal feedback	●◐○	●●○	○	●●●
	Finger-based exploration	●●●	●○○	○	●●●
HYBRID	Interactive tactile maps and diagrams	●◐○	●●●	●	◐○○
	Tangible maps and diagrams	●◐○	●◐○	●	●◐○
	Refreshable tactile maps and diagrams	○○○	●●◐	●	●●●

Figure 2.22. Summary of the main characteristics of *digital* maps and diagrams (above) and *hybrid* maps and diagrams (below). Shaded circles indicate that these characteristics (may) depend on the technology used (e.g. force-feedback devices such as the Phantom are more expensive than a force-feedback mouse).

Because they do not rely on any physical representation, *digital* maps and diagrams can be instantly updated, which is an outstanding advantage. However, this comes at a cost: they must be explored using an input device or one (or two) finger(s), and therefore do not support two-handed exploration. A number of techniques have been developed to compensate for strategies of exploration that rely on multiple hands/fingers (e.g. grid, external memory aids), but the exploration usually remains slow and tedious. The single point of contact nature of these maps and diagrams often lead to the exploration of maps and diagrams that are (very) simple. This is particularly the case with finger-based prototypes that solely rely on audio and vibratory feedback and for keyboard-based prototypes that have mainly been used to explore choropleth maps. However, it should be acknowledged that keyboards can be used to explore diagrams that are hierarchically organized: in that case, the underlying digital content can be relatively complex. Force-feedback devices can convey more complex data, but they are not widespread. Overall, “these limitations [one point of contact] mean that any virtual haptic system is severely impoverished in comparison to the paper-based techniques […]” [196].

Among *hybrid* prototypes, interactive tactile maps and diagrams are undoubtedly the most studied even though a limited number of diagrams have been designed, compared to maps. A number of empirical studies showed that maps and diagrams combining a touch-enabled device or a camera with a tactile overlay and audio output are usable in the absence of vision. Because they rely on the production of tactile overlay by sighted tactile graphic specialists, they are not widely available: however, more and more research projects aim at automating their production, which will make them more widespread. Their main limitation is, as we already discussed, the fact that they cannot be readily updated. On the other hand, refreshable tactile maps and diagrams can be readily updated, but are extremely expensive. In addition, they still have a low resolution and a small size compared to interactive tactile maps and diagrams. In between, tangible maps and diagrams are not too expensive and their content can be updated, as they rely on physical objects that can be easily manipulated by the user or by the system itself. Surprisingly, there is very little work on that topic, making it unclear how complex tangible maps and diagrams might be and how usable they are. Although they are unlikely to reach the complexity of other hybrid maps and diagrams, they are worth investigating as a way to complement other approaches: digital maps and diagrams are updatable and affordable but non-physical; interactive tactile maps and diagrams are affordable and physical but not updatable; refreshable tactile maps and diagrams are physical and updatable but they are also very expensive.

6 CONCLUSION OF PART C

In this part, we first highlighted the lack of a common classification and terminology to designate and describe the various approaches that have been investigated to make interactive maps and diagrams accessible to visually impaired users. Relying on a previous classification by A. Brock [23], we distinguish between two broad categories: *digital* and *hybrid* maps and diagrams [50]. Subcategories of digital maps can be identified depending on the input devices used (regular pointing devices such as keyboards and joysticks; pointing devices with additional force or cutaneous feedback; fingers). Subcategories of hybrid maps can be identified depending on the nature of the physical representation (tactile, tangible or refreshable tactile maps and diagrams). Within each subcategory, we then described a number of representative examples. We also discussed the main characteristics of the proposed approaches, in terms of cost and availability, content, strategies of exploration supported by the prototypes and updatability. Overall, we showed that the single point of contact nature of *digital* maps and diagrams raises several issues, be it in terms of perception or content. *Hybrid* maps and diagrams support two-handed exploration but they are either affordable but non-updatable or updatable but extremely expensive. We therefore highlighted the fact that tangible interfaces, although very rarely investigated for visually impaired users, are very promising as a way to complement existing approaches. In the following parts, we will more thoroughly discuss the properties of tangible interfaces as well as the design challenges they raise when intended for visually impaired users.

PART D

TANGIBLE USER INTERFACES

1 INTRODUCTION

In the previous part, we showed that up to now there has been a lack of research concerning the development of interactive, physical and updatable maps and diagrams for visually impaired users. Because Tangible User Interfaces (TUI) are inherently physical and rely on the use of objects that can be manipulated by the user or by the system itself, they are particularly appropriate to fill this gap. In this part, we review the theoretical background of Tangible User Interfaces and describe their main benefits as well as their inherent limitations. We then describe technologies for the development of tabletop TUIs, before moving on to actuated tabletop TUIs.

2 TANGIBLE USER INTERFACES: DEFINITION AND PROPERTIES

2.1 DEFINITIONS AND RESTRICTION OF SCOPE

The seminal work of Fitzmaurice et al. [65] in 1995 paved the way for research on TUIs. In their article, the authors introduced the concept of Graspable User Interfaces, which “allow direct control of electronic or virtual objects through physical handles for control”. These physical handles, called *bricks,* acted as input devices: for example, by moving or rotating a *brick*, users could move or rotate a virtual object (e.g. a picture) that is attached to it. Unlike traditional Graphical User Interfaces which rely on time-multiplex inputs (e.g. when interacting with a mouse) and space-multiplex outputs (e.g. icons on a virtual desktop), Graspable User Interfaces allow for space-multiplexed inputs as well: each *brick* could be associated with a particular function, allowing for parallel input. The authors identified several advantages of this innovative type of interface, among which the fact that they support two-handed interactions and take advantage of our “everyday skills of prehensile behaviors” and “spatial reasoning skills”. They are also externalized representations and make the elements of the interface more “manipulable”. Despite a number of developments since its publication, the work of Fitzmaurice et al. remains the basis for the design of Tangible User Interfaces.

In fact, the term Tangible User Interface was introduced a few years later by Ishii and Ullmer [113] and referred to interfaces that “augment the real physical world by coupling digital information to everyday physical objects and environments”. The notion of Tangible Bits was also introduced: whereas traditional or “painted” bits rely solely on the visual channel, tangible bits also allow for haptic interaction with the digital environment and take advantage of our “dexterity” and our “skills for manipulating various physical objects”. Therefore, in TUIs “the physical forms serve as both representations and controls for their digital counterparts”.

Since then, TUIs have been developed and studied in a large range of application domains and contexts. The term *Tangible interaction* is even now used as an “umbrella term” [106] that refers to user interfaces focusing on tangibility and materiality, physical embodiment of data, whole-body interactions and embodiment of the interface and of the users' interactions in real spaces and contexts. Couture [40] made the distinction between *tangible close-grained interaction* and *tangible large-grained interaction*. The former relates to interactions within reach of the user's arm, such as manipulating small objects on a tabletop; the latter relates to interactions that require users to move and navigate within large interactive spaces (e.g. rooms) and are therefore out of reach of the user. In this thesis, we will only focus on *tangible close-grained interaction*. More precisely, we will focus on tabletop TUIs, which we define as TUIs that rely on the manipulation of tangible objects over a plane surface.

2.2 TYPOLOGY AND FIELDS OF APPLICATIONS

Ullmer and Ishii [305] identified three main types of TUIs (see Figure 2.23). *Interactive surfaces* rely on a number of tangible objects that are placed and manipulated on a plane surface, which is usually an interactive table augmented with visual feedback (e.g. [126]). *Token+Constraint* systems require the manipulation of tangible objects (*tokens)* that are mechanically constrained by other tangible objects (*constraints)* (see [308] for a review of tokens+constraint interfaces). *Constructive assemblies* are similar to building blocks such as LEGO, i.e. they are composed of a number of tangible objects that are attached to each other (e.g. [246]). Although very helpful to broadly categorize TUIs, this typology is limited by the fact that one TUI may straddle two or three categories. For example, the tabletop TUI that we describe in Chapter 3 relies on several tangible objects placed above a tabletop (*interactive surface)*, some of which are connected to each other to create a map or a diagram (*constructive assemblies)*.

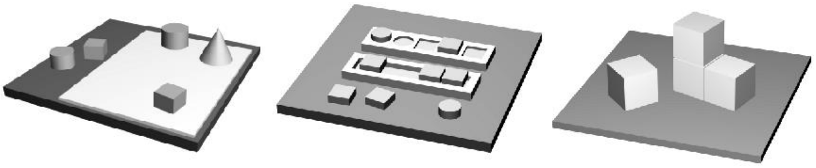


Figure 2.23. Illustrations of three main types of TUIs. Left: interactive surfaces. Middle: token+constraints. Right: constructive assemblies. Retrieved from [308]**.**

These different types of TUI have been used in a wide range of disciplines. Shaer and Hornecker [276] identified eight application domains: 1) TUIs for learning, which mainly include augmented construction kits and building blocks (also referred to as *digital manipulatives)*, tools for storytelling and tools to assist children with special needs; 2) TUIs for problem solving and planning that are particularly adapted to spatial or geometric applications such as urban planning, simulations or scheduling (see Chapter 2, Part D, 2.4.2); 3) TUIs for information visualization that are more often intended to professionals such as geophysicists (e.g. [41]); 4) TUIs for programming (e.g. [220]) ; 5) TUIs for entertainment, play and edutainment; 6) TUIs for music and performance, with the well-known example of the ReacTable [126], a tabletop TUI in which tangible objects are assigned particular functions (such as filtering audio, generating sound) and that support the creation or editing of music; 7) TUIs for social communication, where objects are used at the periphery of the user's attention (e.g. [20]); 8) tangible reminders and tags (e.g. [102]).

As pointed out by Shaer and Hornecker [276], these application domains are not mutually exclusive. In our case, tangible maps and diagrams can mainly be used for learning as well as for problem solving or information visualization, but they could also be used for entertainment or edutainement.

2.3 FRAMEWORKS AND TERMINOLOGY

Shaer and Hornecker [276] provided an exhaustive review of frameworks and taxonomies that have been proposed to structure and formalize the field of TUIs. Instead of describing each of these theoretical contributions, we detail the ones that we will later rely on to discuss and compare existing prototypes of tangible maps and diagrams for visually impaired users.

2.3.1 INTERACTION MODEL OF TUIS

Perhaps the most well-known interaction model of TUIs is the one proposed by Ullmer and Ishii [305], which draws from the traditional Model View Controller for Graphical User Interfaces (GUI). In this model entitled Model Controller Representation (intangible and tangible), or MCRit, the emphasis is put on the fact that the digital model is rendered using both tangible representations (e.g. physical artefacts) and intangible representations (e.g. projected images and sounds). The tangible representation is closely coupled to the underlying digital information and model (Figure 2.24, left). It also acts as a physical control, whereas in traditional GUIs the input and output spaces are not unified [111]. Because the tangible representation is less malleable than the digital model (due to the use of physical artefacts), intangible representations are used to expand the expressiveness of the tangible representations. The main consequence of using both tangible and intangible representations is that TUIs provide at least two feedback loops [111] (Figure 2.24, right). First, users receive feedback whenever they touch, grasp or release a physical artefact–this is the *passive haptic feedback loop*, which is immediate and does not rely on any digital process. Then, the interface provides feedback through the intangible representation, depending on the action performed by the user–this is the *digital feedback loop* that relies on a digital process. A third loop can be provided, called *physical actuation*, which we will more thoroughly describe in section 4.

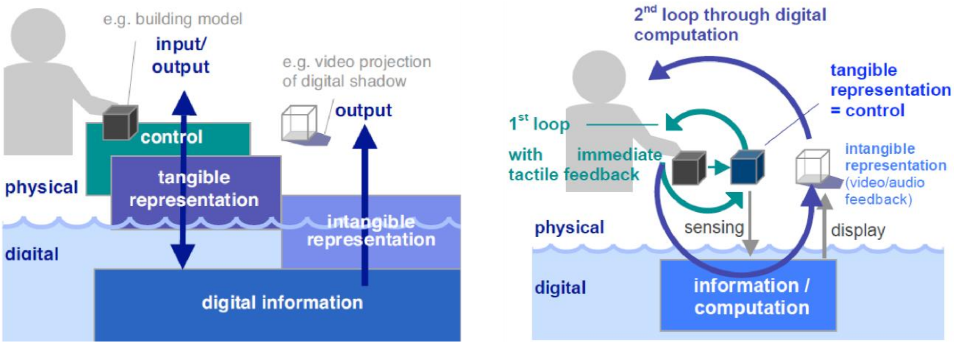


Figure 2.24. Left: the Model-Control-Representation (intangible and tangible) or MCRit model of TUIs [305]**. Right: TUIs provide at least two feedback loops. (Illustrations retrieved from** [111]**).**

2.3.2 DESCRIPTION OF TUIs

The components of a TUI, and particularly of its tangible representation, can be described using a number of terms (see [276] for an extensive review of frameworks, taxonomies and models). Two well-known frameworks have been proposed by Holmquist et al. [102] and Shaer et al. [277]. To illustrate them, we use the following very simple example: a tabletop TUI enables user to explore a map displaying the main cities of a country. Tangible objects are used to represent the cities. One particular object can be used for zooming when placed inside a rectangular area surrounded by a physical frame (the zooming area) or for displaying the number of inhabitants when placed next to a city. Several tiles are placed next to the table and each tile represents a map of a country: users can explore the map of a country by choosing the corresponding tile and placing it on the table.

The paradigm proposed by Shaer et al. [277] can be used to precisely describe the core elements that compose a TUI and is based on four concepts: *pyfo*, *token*, *constraint* and *TAC*. A *pyfo* is simply a physical object that is part of the TUI: in our example the tiles, the physical cities, the object for zooming and the physical frame surrounding the zooming area are all pyfos. A *token* is a pyfo that is bound to digital information. When the object for zooming is placed on the edge of the tabletop, it is simply a pyfo. As soon as the user places it within the zooming area, it becomes a *token,* which is coupled to a *variable*. In our case, the variable is the scale of the map. A *constraint* is "a pyfo that limits the behavior of the token with which it is associated". In our case, the zooming area is a *constraint*. Finally, a TAC is a relationship between a *token*, its *variable*, and one or more *constraints*. A new TAC is created whenever a token is physically associated with a constraint (e.g. when the "number of inhabitants tool" is placed next to a city). The physical manipulation of a TAC (either continuous or discrete) has computational interpretation. For example, moving the zooming tool (continuous interaction) results in changing the scale of the map; placing a new tile (discrete interaction) results in loading a new map.

Holmquist et al.'s [102] taxonomy focuses on the links between the tangible objects and the digital information: "*containers* are generic objects used to move information between different devices or platforms; *tokens* are used to access stored information, the nature of which is physically reflected in the token in some way; and *tools* are used to manipulate digital information". In our example, the tiles representing the maps are *containers*–each digital map is attached to one of the physical tiles; the objects representing the cities are *tokens;* the tangible objects used for zooming or displaying the number of inhabitants are *tools*–by rotating it, users can manipulate the scale of the map; by placing it next to a city, they can invoke the function "number of inhabitants".

Although the TAC paradigm is useful to identify and describe the core elements of a TUI, the taxonomy proposed by Holmquist et al., which does not serve the exact same purposes, is very easy to apprehend. Therefore, in the remaining of this thesis, we will rely on Holmquist et al.'s taxonomy and when necessary we will refer to physical objects as *tokens*, *tools* or *containers*. Otherwise, we will simply use the term *tangible objects* to highlight the fact that the objects are physical and that they are used in the context of a TUI.

2.4 ADVANTAGES AND LIMITATIONS OF TUIS

Since the very beginning of research on Graspable or Tangible User Interfaces, essential properties have been identified and studied. Throughout the years, the development of a number of prototypes has also enabled researchers to further investigate the benefits of TUIs in terms of cognition[28] and possible uses. In this section we briefly review the main contributions of TUIs: we first focus on properties that are inherent to TUIs and independent of their application domain, before discussing their potential for collaborative, learning and spatial applications. Although we distinguish between advantages in terms of interaction and cognition, they are intrinsically related to each other.

2.4.1 ADVANTAGES OF TUIS IN TERMS OF INTERACTION

Ishii [111] identified five advantages of TUIs over Graphical User Interfaces (GUIs). We already discussed the first one, which concerned the **double interaction loop** that provides immediate tactile feedback, which is not the case with GUI. The second advantage is the **persistency of tangible objects**: their position relative to each other as well as their orientation, shape and color can help users to know what the current state of the digital model is. Even if the system is turned off, the tangible objects still convey basic information about the purpose and state of the system. The third advantage is the **coincidence of input and output spaces:** users do not need to look at an additional screen and tangible objects can be used as direct input devices. If the objects move or if visual feedback is projected on or around them, they can also serve as output devices, therefore allowing for a spatial continuity between input and output spaces. The fourth property of TUIs, which is both an advantage and a disadvantage, is that they are **special-purpose interfaces**, unlike GUIs that are general-purpose interfaces. As tangible objects are generally designed to fit a particular function or to represent a certain piece of information (e.g. a building model) they can rarely be adapted to several applications. This specificity allows TUIs to "increase the directness and intuitiveness of interactions". However, a compromise must be found between designing very abstract tangible objects that do not convey any *affordance* and designing special-purpose objects that cannot be re-used in another application. The fifth and last benefit of TUIs is that they allow **space-multiplexed inputs**. Since each object can be assigned a particular function, several users can interact with several objects at the same time, therefore "allowing concurrent manipulation of information", which is not possible with GUIs that only allow for time-multiplexed inputs.

As we said in section 2.1, these contributions are closely linked to the properties identified by Fitzmaurice et al. [64] when designing the first Graspable User Interfaces. However, it is worth mentioning that Fitzmaurice emphasized the idea that Graspable User Interfaces involved the use of two hands, as compared to GUIs, which mainly use two hands for typing. He also emphasized the fact that both the position and the orientation of the tangible objects are "critical pieces of information" and must be tracked using a sensing system. By doing so, it is possible to develop spatially-aware devices that are more spatial than alpha-numeric and are therefore more adapted to graphical tasks. The last property mentioned is the spatial reconfigurability of the elements.

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[28] In this section, the term "cognition" is taken in a broad sense to refer to different theories (embodied and distributing cognition) and process (learning, acquisition of spatial knowledge, etc.)

Finally, it should be mentioned that the notion of special-purpose interfaces is closely related to the idea of *affordance*. Because the tangible objects are defined by a set of attributes such as their shape, size, texture, etc., they provide strong affordances that help users understand how they should be interacting with them. In other words, tangible objects "cue" interactions [276].

2.4.2 ADVANTAGES OF TUIS IN TERMS OF COGNITION AND USE

Theories of embodied and distributed cognition emphasize the role of physical objects and environments in constructing knowledge. In that sense, TUIs appear to be particularly relevant as tools for the construction of knowledge. TUIs also proved relevant for collaborative, learning and spatial applications. Instead of providing an exhaustive review of studies that investigated the benefits of TUIs, we only highlight the main properties of TUIs that may explain their successful use for these types of applications.

EMBODIED COGNITION

Theories of embodiment emphasize the role played by the body in the understanding process. Embodied cognition, which originates from cognitive sciences, acknowledges the fact that humans are not "abstract cognitive entities" and that "our bodies and active bodily experiences inevitably shape how we perceive, feel, and think" [276]. Whereas GUIs barely make demands upon our body (except for moving the mouse or typing), TUIs allow for tactile and haptic experiences. When users move around interactive set-ups, their whole body is engaged. The embodiment of interaction can have several benefits. For example, we already extensively discussed the benefits of two-handed exploration as compared to single finger exploration. Jetter et al. [124] gave numerous examples of studies that demonstrated that the use of hand or arm movements can have a positive effect on working memory, and possibly on spatial memory. Reviewing studies pertaining to the field of Embodied cognition would be beyond the scope of this thesis; nevertheless, the four key ideas discussed by Kirsh [139] provide a good overview of the potential benefits of embodiment:

> *"1) interacting with tools changes the way we think and perceive–tools, when manipulated, are soon absorbed into the body schema, and this absorption leads to fundamental changes in the way we perceive and conceive [of] our environments; 2) we think with our bodies not just with our brains; 3) we know more by doing than by seeing–there are times when physically performing an activity is better than watching someone else perform the activity, even though our motor resonance system fires strongly during other person observation; 4) there are times when we literally* think *with things"*

DISTRIBUTED COGNITION

In Part A, we particularly discussed the benefits of external representations, for example for problem-solving tasks. With TUIs, the tangible representation of the digital model can also act as an external representation, and as such present the same advantages as those we already mentioned, such as *computational off-loading* or *graphical inferences*. In our example of the tangible map, the use of a tactile frame around the zooming area also constrains how the user can interact with the system as well as the minimum and maximum scale of the map, therefore sparing the user having to select a scale that would result in displaying a map too magnified to be legible. The difference is that, unlike print representations that cannot be manipulated, the elements of the external and tangible representation can be physically manipulated. Therefore, TUIs may raise further advantages. In particular, tangible objects may serve as "thinking props" and support epistemic actions that help users explore options [276], such as rearranging or removing tangible objects [29]. This echoes the fundamental aspects of the *distributed cognition* theory, which emphasizes the fact that cognition is not purely internal but is distributed across the members of a social group and, more relevant in the case of TUIs, involves coordination between an internal and external (material or environmental) structure [101].

SPATIALITY

A key element of TUIs is their inherent spatiality. Shaer and Hornecker [276] noted that TUIs are particularly adapted to spatial or geometric applications as the arrangement of the tangible objects is closely linked to the digital model (e.g. a map). Sharlin et al. [279] particularly investigated how TUIs exploit "human spatiality, our innate ability to act in physical space and interact with physical objects" and defined *spatial TUIs* as TUIs that "mediate interaction with shape, space and structure in the virtual domain".

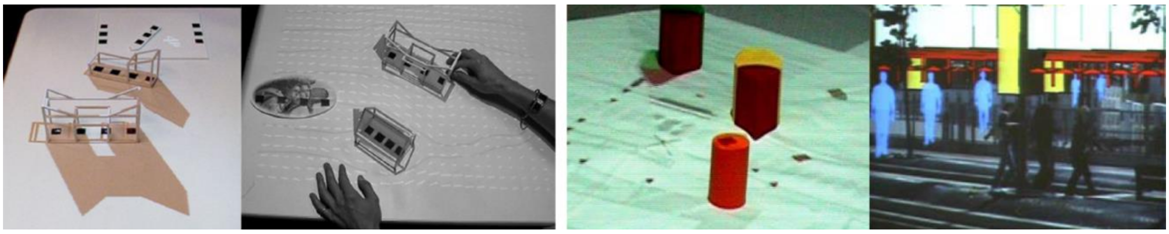

Figure 2.25. Two TUIs that enable urban planners to interact with a map by simulating wind flow, sunlight, pedestrians, etc. Left: Urp (retrieved from [310]**). Right: the ColorTable (retrieved from** [184]**).**

A large number of spatial TUIs have been developed to enable sighted users to interact with a map. GeoSpace [113] was an interactive map of the MIT Campus designed for sighted users, where physical objects were used to pan or zoom by forcing the digital map to reposition itself. Urp [310] allowed sighted urban planners to simulate wind flow and sunlight (Figure 2.25, left). It was used to observe their consequences on models of buildings placed onto the tabletop. With the MouseHous Table [107], users could simulate several arrangements of urban elements such as streets and buildings. Paper rectangles were placed on the device and helped to visualize the behavior of pedestrians around the buildings. Similarly, the ColorTable [184] was a tool to aid urban planners and stakeholders in discussing urban changes (Figure 2.25, right). In that project a mixed-reality scene was created from the original map and the tangible objects that had been placed above it. The potential of TUIs for geospatial applications has also been discussed in a number of publications (e.g. [125,249]).

Interestingly, applications that are not inherently spatial can also be adapted to be represented by tangible objects whose spatial arrangement becomes meaningful [276]. For example, although storytelling is not inherently spatial, a number of TUIs for storytelling have been developed (e.g. [290]): the different parts of the story can be embedded into tangible objects whose relative positions indicate the course of events (similar to flow charts).

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[29] More precisely, epistemic actions are "actions performed to uncover information that is hidden or hard to compute mentally" [140].

Finally, it should be mentioned that TUIs may also improve spatial cognition. In a well-known study, Kim and Maher [137] asked designers to solve space-planning problems (redesigning existing studios into a home office and a design office). Two conditions were compared: using a TUI composed of 3D blocks vs using a GUI with a mouse and keyboard. Results indicated that the participants' spatial cognition[30] was better in the TUI condition than in the GUI conditions. In fact, participants proposed more ideas and investigated more alternatives in the TUI condition; they also engaged in larger gestures, which may have helped them feel more immerged and may have helped them to better structure their spatial cognition. Also, the authors observed that participants paid more attention to spatial relationships between the pieces of furniture in the TUI condition.

LEARNING (BY DOING)

TUIs have been largely used for learning. Shaer et Hornecker [276] identified four reasons: augmenting physical objects can "increase their functionality and attractiveness"; TUIs engage all senses and may support the child's development; gestures facilitate thinking and learning; TUIs are particularly suited for simple examples that do not require scaling or manipulating large sets of data, i.e. for novices. Marshall [188] and O'Malley and Fraser [218] also identified possible benefits of TUIs for learning. For example, enabling people to access a different representation can change the nature of knowledge, and possibly make it easier to grasp a new concept or idea. Piaget's theory also stipulated that the manipulation of objects could develop thinking [235], and corroborates the observations made by Montessori about children being "attracted" to sensory development materials [209].

Based on similar considerations a number of TUIs have been developed, be it for storytelling (e.g. [262]), programming (e.g. [220]) or visualization of molecular structures [76]. However, Marshall [188] pointed out that these tasks could also be supported by traditional GUIs and that it is unclear whether using TUIs for such application domains actually facilitates learning in comparison with GUIs. In fact, when reviewing a number of empirical studies that had compared TUIs and GUIs for learning, Schneider et al. [271] found that results were mitigated and concluded that "even if these studies are not enough to prove that tangible material is not improving learning, it indicates that tangibility alone may not be a panacea". They also posited that benefits should not be measured in terms of learning only and that "accessory benefits like enhanced collaborative learning, increased engagement, playful learning, etc." should also be considered. Interestingly, Marshall [188] suggested two types of learning activities where TUIs could outperform GUIs: in *exploratory activities*, learners can explore an existing representation and manipulate some parameters in order to observe how they impact the representation; in *expressive activities*, learners create their own representation and can use it to, for example, work out whether the reconstructed representation reflects the real problem or not. To sum up, even though more studies are required to better understand how TUIs could enhance learning when compared with GUIs, it appears that TUIs can support various learning activities (and especially exploratory and expressive activities) by making them, if not always more beneficial, at least more playful and/or engaging [271].

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[30] In the article, the authors use the term "spatial cognition" to refer to the process of "perceiving and reasoning about visuo-spatial information in an external representation" [137].

COLLABORATION

Non-tangible interactive surfaces provide many advantages when used in a collaborative context. They are designed for co-location, multiple users, hands-on activities and multiple modes of communication (e.g. talk, gaze) [46], which can be particularly helpful when several users are collaborating. Tabletop TUIs provide the same advantages. However, the use of tangible objects can provide additional benefits. Hornecker [105] discussed the idea of Embodied Facilitation by considering to what extent the inherent properties of a collaborative TUI can facilitate some behaviors or actions. Three concepts were introduced: *embodied constraints*, such as the shape of the table or the number of tools provided, can constrain the users' behavior and lead them to collaborate; *multiple access points* can ensure that all users can access the tangible objects that are required to perform the task; *tailored representations* build on users' experience and encourage them to interact with the system, lowering the threshold for participation [106]. Some benefits of TUIs that we previously described are particularly relevant in a collaborative context. For example, users can exchange objects in order to perform a particular action, which allows for fluid interactions. Furthermore, users can see what the other users are doing, allowing for a high level of *awareness* (e.g. [291]). In particular, the manipulation of tangible objects by a user can be easier to perceive and to interpret as compared to a multitouch gesture.

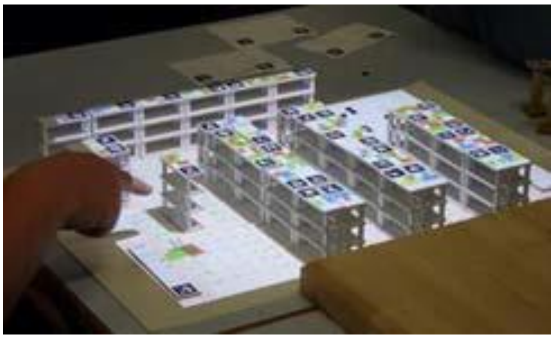

Figure 2.26. The prototype used by Schneider et al. [271] **to investigate the benefits of TUIs for collaborative learning. Retrieved from** [271]**.**

A number of studies have been led to investigate the benefits of TUIs in terms of collaboration, and particularly in terms of collaborative learning. For example, in the study proposed by Schneider et al. [271] a TUI was compared to a multitouch interface (Figure 2.26). Results show that for the same problem-solving task (arranging the layout of shelves in a warehouse), using the TUI was beneficial in terms of performance (a higher number of accessible shelves), subjective rating of playfulness, and collaboration (a higher collaboration score, measured with a questionnaire). In fact, participants explored more alternative solutions with the TUI than with the multitouch interface. It is probable that the physicality of the small-scale shelves encouraged participants to manipulate them. In a study by Speelpenning et al. [288] two groups of participants played a game about sustainable development, using a multitouch application of a TUI. Although performances were similar between the two interfaces, the authors reported that under the TUI conditions, participants achieved a higher *awareness*.

2.5 LIMITATIONS

The main limitations of TUIs are due to the use of real physical objects that are rigid and static, as compared to their digital counterparts. From a practical perspective, tangible objects need to be stored, in contrast do digital objects that do not take up physical space. There is therefore a risk of losing or misplacing them [276]. Tangible objects are also less durable than digital objects: they can break or be physically altered when used several times. In particular, fiducial markers attached under or over the objects may need to be regularly reprinted to ensure a reliable tracking. There is also a need to make and build these objects. Even though everyday objects can be used, it is very often necessary to adapt them, for example by affixing a fiducial marker.

As far as the tangible representation is concerned, the main issue is *scalability* [276]. Because a limited number of tangible objects can be used on a single surface, TUIs are not particularly adapted to represent complex problems or models, even though visual feedback can be used to increase the expressiveness of the representation. This is related to the notion of "structural correspondence" introduced by Edge and Blackwell [55]. The physical structure and the information structure that are represented should provide similar possibilities in terms of interaction. However, because the design of physical objects is constrained, they may not support interactions or manipulations as complex as those offered by digital objects. For example, tangible objects are usually fixed in size and therefore cannot be enlarged and reduced dynamically (e.g. by zooming in or out), unlike digital objects. Increasing the number of tangible objects can also lead to "physical clutter" [276], which can make the tangible representation less legible or more difficult to understand. Although it could be possible to increase the size of the surface itself, this should not result in participants having difficulty in reaching all objects without having to move.

We already briefly indicated that the fact that TUIs are specific-purpose (or strong-specific [276]) could be seen as both an advantage and a disadvantage. If tangible objects are specifically designed for a particular TUI, they can rarely be used for another TUI. Although it is possible to design generic and abstract tangible objects, one should keep in mind that the affordance of the objects is one of the key contributions of TUIs in terms of interaction. This raises an issue of *versatility* [276]: not only can a TUI rarely support a wide range of tasks, but for a single task TUIs can hardly support functions that require a dynamic reconfiguration of the representation, such as undoing/re-doing actions.

Another limitation is correlated to the technologies used for implementing tabletop TUIs. As we will see in the following section, tabletop TUIs can be very low-cost when they only rely on a webcam, a transparent surface and some objects, but they can also require additional hardware when finger tracking is necessary and/or when there is a need to display or project visual feedback. Therefore, the choice of implementation technologies impacts the affordability and availability of tabletop TUIs. In fact, to date, tabletop TUIs are most often used in laboratories or intended for a public audience (e.g. in museums). However, the development of commercialized systems such as the ReacTable [126] suggests that in the future tabletop TUIs will be more widespread and easier to implement.

3 TECHNOLOGIES FOR TABLETOP TUIS

Since the first TUIs various technologies and toolkits have been used and developed to build tabletop TUIs [276]. However, although a few commercialized solutions exist, most research projects still rely on the use of custom-made prototypes whose cost, reliability, features and ease of assembly can vary greatly depending on the technologies used. In this section we give an overview of these technologies. More specifically, we describe technologies used for 1) tracking and identifying tangible objects, which is the basic feature of TUIs; 2) detecting users' touches, which can greatly enhance how users can interact with the system; 3) displaying or projecting visual feedback onto the table. Even though visual feedback is not essential for visually impaired users, it can promote collaboration between visually impaired and sighted users and, as we discussed in Chapter 2, Part E, 4.2, can be particularly helpful for users with low vision.

3.1 TRACKING OBJECTS

Voelker et al. [323] identified four requirements for tabletop TUIs: 1) at any one time, the system must know which tangibles are currently on the tabletop; 2) each tangible object must have a unique ID; 3) the system must know the position and orientation of each tangible object; 4) fast-moving tangible objects should be detected without noticeable delays. Additional pieces of information may also be useful to increase the design space of interaction techniques on and above the tabletop, such as detecting the z-position of the tangible objects and knowing whenever the user is touching or interacting with a tangible object.

Among the various technologies that aim at fulfilling these requirements (or at least at obtaining the x- and y- positions of the tangible objects), two main techniques can be identified [80]. The first (and the most common) relies on external sensing, i.e. the tangible objects are being tracked by an external device such as a camera; the second, less frequent, relies on internal sensing, i.e. the objects themselves are aware of their position, orientation etc., and send the corresponding information to a central unit that provides feedback accordingly. In this section we describe existing technologies for external and internal sensing. Although the list is not exhaustive, it covers common technologies that have been applied to a large number of prototypes.

3.1.1 EXTERNAL SENSING

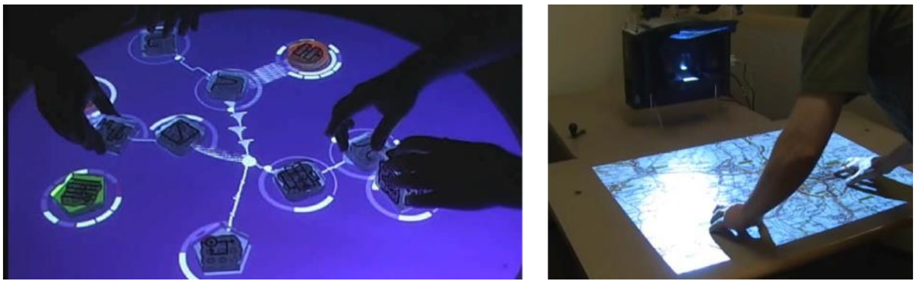

Figure 2.27. Two examples of camera-based systems. Left: with the ReacTable, the camera is placed below the surface (retrieved from [126]**). Right: in PlayAnywhere, the camera is placed on the side of the table (retrieved from** [341]**).**

In this technique two types of system exist, depending on whether they rely on cameras or other types of electromagnetic sensors. **Camera-based systems** rely on computer vision algorithms to detect, identify and track tangible objects. Although tangible objects can be detected and identified based on their shape, size or color (see [184] for example), the main approach is to attach a *fiducial marker* to the top of or below the objects (as in the Reactable [126], Figure 2.27, left). When a marker is detected in the image, the corresponding software library provides the position and identity of the object and, in most cases, its orientation. The camera is usually placed above or below the tabletop, although in PlayAnywhere [341] the camera is placed on the side of the table (Figure 2.27, right). Cameras can be in the optical or infrared domain. The advantage of using infrared cameras is that the algorithm operates in a different spectrum to the one used for projecting an image onto the tabletop, therefore avoiding the projected image interfering with the detection of tangible objects [274]. Another way to detect tangible objects in the infrared spectrum is to use LEDs. For example, TouchBugs [217] are small objects that embed two LEDs that are detected by a camera placed under the surface: the frequency and amplitude of the light signal allow the application to detect the objects, as well as their position and orientation. Tags can also be composed of a number of reflective markers: for example, SlapWidgets [336] are made of silicone, making them compliant with a finger-tracking technology (FTIR, see 3.2) that cannot be used to track fiducial markers.

A variety of systems based on **electromagnetic sensors** have been developed[31]. One of the most common technologies is *RFID* (Radio-Frequency Identification) [276]. RFID tags are embedded into the tangible objects and their presence can be detected when they are within range of a tag reader connected to a computer. The RFID tags can be passive, in which case they can emit their identity only when they are powered by the tag reader (wirelessly, via induction) or active, in which case they are self-powered and emit a constant signal. Several tabletop TUIs rely on a matrix of RFID antennas (e.g. [116,307]).

Tangible objects can also embed magnets. In this case, a dedicated hardware is used to detect the magnetic fields of the tangible objects. Specific algorithms are therefore applied to identify the objects based on the variations of the magnetic fields. For example, in GaussBricks [167], an analog Hall-sensor grid was attached under a tablet and was used to detect the overall shape and structure of constructions made of different types of tangible and magnetic bricks (Figure 2.28, left).

Although originally meant to be used for tracking fingers, *capacitive* surfaces can also be used to detect tangible objects. The idea is to simulate touch inputs, usually with passive and conductive "tags" (such as a metallic tack). The layout of the tags is used to identify the objects, as well as their orientation, and ensure that the objects can easily be distinguished from finger touches. Recently, Gonzalez et al. [210] proposed TouchTokens, which are tangible objects whose shape restricts the way that users can grasp them (Figure 2.28, right). By detecting the positions of the fingers that hold the object, the system is able to identify which object is being manipulated. Another approach proposed by Götzelmann and Schneider [88] and called CapCodes, is to 3D-

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[31] Although RFID, electric and magnetic technologies are often presented in different categories, they are all related to the use of electromagnetic fields, hence our choice to present them in the same category (see https://en.wikipedia.org/wiki/Electromagnetic_field)

print objects with conductive elements. When placed above a capacitive surface and touched by the user, the system can detect the position and orientation of these objects by analyzing the "touch" positions.

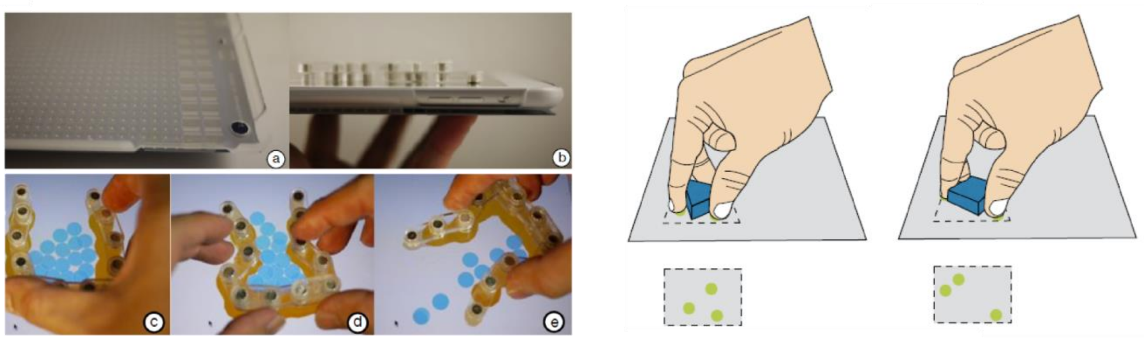

Figure 2.28. Two examples of systems based on electromagnetic sensing. Left: in GaussBrick, an analog Hall-sensor grid was attached under a tablet and enabled the system to track small objects/magnets (retrieved from [167]**). Right: TouchTokens constrained how the user can grasp them: the finger positions is then used to retrieve the ID of the tangible object with a capacitive surface (retrieved from** [210]**) .**

3.1.2 INTERNAL SENSING

In this section, we only refer to tangible objects that embed sensors that allow them to communicate their position (and orientation) to the main application. Stand-alone systems that are "aware" of their 2D or 3D topologies are therefore not considered (see [80] for a brief review of illustrative examples). The main approach for internal sensing is the use of integrated sensors that detect what is displayed under or above the tangible objects and use this piece of information to compute their position and orientation. For example, Zooids [81] are small robots that are equipped with two photodiodes that are used to decode gray-coded patterns projected over the table. Cellulos [223] are robots equipped with a camera that is used to decode micro-dot patterns printed on paper. Each pattern encodes a unique and absolute position. These approaches are based on the Anoto[32] technology which is often used to track the position of a stylus on a sheet of paper.

3.1.3 COMPARISON OF EXISTING TECHNOLOGIES

External sensing devices range from a very simple set-up (e.g. a camera placed below a glass table) to more complex ones (e.g. RFID sensing including an array of antennas). Although systems based on electromagnetic sensors may contain interesting features (e.g. GaussBricks [167], which could be used on a tablet), they are generally expensive and difficult to assemble. Besides, RFID technology does not provide the orientation of the tangible objects while systems that rely on the analysis of magnetic fields do not usually provide their identity [276]. Camera-based devices are usually cheaper and easier to assemble. Besides, computer-vision algorithms for tracking fiducial markers are fast and accurate, even though a delay may be observed when tracking movable objects [276]. A downside to these devices is that they depend on lighting conditions and that

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[32] http://www.anoto.com/

they can be quite bulky. Also, it should be noted that all tabletop TUIs based on a tracking system from above the surface are sensitive to hand occlusions.

Tangible objects that are adapted to be tracked with capacitive or inductive surfaces are a good alternative, notably in terms of cost. However, with this technology most tangible objects are only detected when the user touches them. To tackle this issue it is possible to add sensors within the objects, which can be used to detect whether they are touching the surface or not (e.g. [323]). Although the integration of electronic devices makes it more difficult to assemble the objects, it is a promising solution. However, because the objects are designed so as to simulate touch inputs whose configuration creates a unique pattern that can be identified ("footprints"), they are usually relatively large and/or only a limited number of tangible objects can be used.

As for tangible objects equipped with a camera (internal sensing), they can achieve a very high accuracy in terms of localization and can be relatively small. However, each tangible object needs to be self-assembled and lighting conditions may be an issue. The main advantage of internal sensing over external sensing is that no external camera needs to be used, which results in set-ups being less bulky than traditional TUIs.

3.2 TRACKING FINGERS

Technologies for tracking fingers can be categorized into camera-based systems or electric surfaces [274]. Similarly to the previous section, we do not provide an exhaustive list but cover the most common solutions, based on the technical report by Schöning et al. [274].

3.2.1 CAMERA-BASED SYSTEMS

Fingers can be tracked by using appropriate computer-vision algorithms and a *regular camera* (in the optical domain) or a *motion-capture system*. Motion-capture systems make it possible to not only track and identify fingers, but also to retrieve their z-position. However, the most common approach to track fingers is to place a camera below a surface which is illuminated using infrared LEDs [274]. Two main technologies can be implemented by varying the position of the IR LEDs and by using different materials. *FTIR* (Frustrated Total Internal Reflection) set-ups are composed of a transparent acrylic pane surrounded by a frame of infrared LEDs that emit light inside the surface (Figure 2.29, left). When the user touches the pane, the light "escapes" and is refracted at the position of the finger; the resulting reflections can be detected by the camera [274]. *DI* (Diffused Illumination) set-ups are composed of infrared illuminators that are placed below the surface (Figure 2.29, middle). When an object or a finger touches the surface that diffuses the light, infrared light is reflected and detected by the camera as it produces a "blob" that is brighter than other areas [274]. *DSI* (Diffused Surface Illumination) set-ups are very similar to DI set-ups, but a special material is used that prevents the need to place infrared LEDs below the surface, making the set-up less bulky [274] (Figure 2.29, right). *Infrared frames* can also be placed above various surfaces: they are composed of LEDs that create an "infrared grid" and of light detectors. When the user touches the surface surrounded by the infrared frame, the finger intersects the rays and the corresponding light detectors no longer receive a signal. From this, the position of the finger within the frame can be computed.

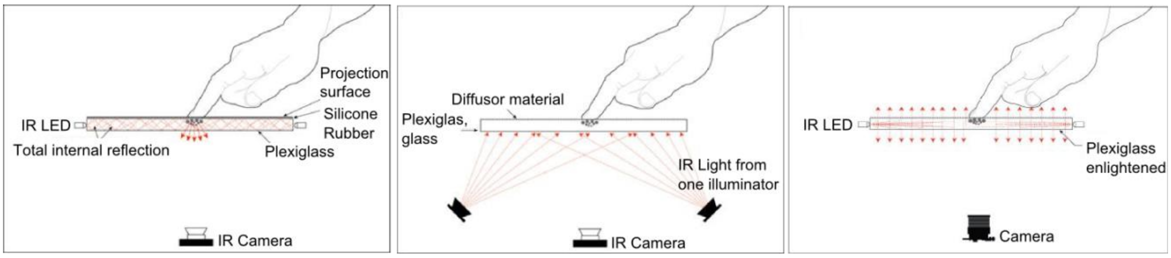

Figure 2.29. Finger-tracking with camera based systems. Left: Frustrated Total Internal Reflection. Middle: Diffused Illumination. Right: Diffused Surface Illumination. (after http://wiki.nuigroup.com/Hardware)

3.2.2 ELECTRIC SURFACES

Electric systems mainly consist in *resistive surfaces* or *capacitive surfaces* [274]. Resistive surfaces are composed of two conductive layers separated by an insulating layer. When users touch the display, the two layers touch each other and establish a current that is measured in order to obtain the position of the touch input [274]. Capacitive surfaces are composed of a single conductive layer and electrodes around the edges that ensure a uniform electric field across the layer. When a user touches the surface, there is a transfer of charge from the layer to the user, which results in a deficit of charge that can be measured and accurately localized [274]. *Projected* capacitive surfaces are composed of two layers of glass inside which a grid of conductive material is installed. When the user touches one glass layer, the difference of capacitance can be computed to locate the touch input [274]. Interestingly, *capacitive foils* are now available on the market: they consist in a very thin, transparent and flexible film that can be attached to any non-metallic surface to transform it into a multitouch surface.

3.2.3 COMPARISON OF EXISTING TECHNOLOGIES

FTIR technology is very efficient for tracking fingers but cannot be used to track fiducial markers [274]. DI and DSI technologies support both fingers and objects tracking, but they can require a relatively complex calibration and set-up (projector, IR LEDs, material used, etc.). Their cost can vary extensively, depending on whether they are "do-it-yourself" prototypes or commercialized. Interestingly, open source toolkits such as CCV[33] are numerous and provide basic features for detecting the position of fingers as well as the input state (pressed, moved or released). Capacitive and resistive surfaces are usually integrated in tablets or multitouch displays, sparing the need to assemble them and to buy dedicated hardware. Infrared frames and capacitive foils are now available on the market: they are very easy to assemble, relatively cheap and can be used with a large range of surfaces. However, they are less accurate and, in the case of infrared frames, the use of tangible objects can interfere with finger tracking as the objects intercept the infrared rays. A more detailed comparison of existing solutions for multitouch surfaces can be found in Schoning et al [274].

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[33] http://ccv.nuigroup.com/#home

3.3 VISUAL FEEDBACK

To display the visual representation of the user interface upon the surface, two solutions can be considered: using a projector (beamer) or a LCD screen [274]. The projector can be placed below the surface (rear-projection) or above the surface (front-projection). Depending on the projector throw (i.e. "the distance between the projector and projection surface which is required to display an image of a specific size" [274]), a system of mirrors can be used to reduce the height of the table. Depending on the material of the surface it may also be necessary to use an additional layer onto which the image will be projected. LCD screens can also be used but must be adapted by removing some layers when a camera is used to detect the user's fingers from below the screen.

3.4 SUMMARY

To sum up, technologies for tracking tangible objects vary in cost, from very low-cost set-ups that only use a camera and fiducial markers to expensive ones that rely on grids of electromagnets. Also, they do not offer the same features: for example, RFID technologies do not recognize orientation while technologies based on magnetic fields do not recognize identity. However, as mentioned by Voelker et al. [323], being able to detect the position, identity and orientation of tangible objects is essential. Therefore, the most common and affordable approach is to use fiducial markers tracked by a camera. Technologies based on internal sensing are very promising but they require the objects to be self-powered and are more difficult to assemble. Similarly, technologies for finger tracking vary in cost but also in accuracy: for example, infrared frames and capacitive foils are not as precise as camera-based devices. However, the use of a camera can be an issue because it requires calibration and, when placed above the tabletop, can lead to occlusions of the tangible objects. Although most technologies only provide the x- and y- positions of the tangible objects and fingers, exploiting the z- position can enhance the design space of interaction on and above the tabletop (e.g. [95,187]).

Issues arise when trying to combine finger and object tracking with visual feedback. In fact, very few prototypes have implemented these three functionalities: most tabletop TUIs do not support touch interaction. To combine these functionalities, the most common approach is to place an infrared camera below the tabletop and to use Diffused (Surface) Illumination to track both the fingers and the fiducial markers. To project an image onto the screen an additional projection surface is required. However, this surface "blurs" the image perceived by the camera and therefore fiducial markers must be large enough to be recognized (around 4 cm wide). In SlapWidgets [336], the authors combined FTIR (for touch detection) with DI (for object detection). However, they did not use fiducial markers but silicone-based markers that created a unique "footprint" for each object. A few commercialized interactive tables exist that combine a screen (to display the image) with multitouch and object tracking. Microsoft Surface supported the tracking of relatively small tags (around 3 cm diameter) consisting of several infrared reflective and absorbing areas. However, this product has been discontinued. Multitaction tables are composed of several infrared cameras placed inside the table, but tracking objects less than 4 cm wide is very difficult to achieve.

4 ACTUATED TABLETOP TUIs

4.1 DEFINITIONS AND MOTIVATIONS

When tangible objects are used as tokens issues arise when the physical representation must be updated to reflect a change that occurred in the digital model. Indeed, most tabletop TUIs rely on tangible objects that are passive and can only be manipulated by the user. Even though users can move the tangible objects to their new position, this takes some time when several objects need to be displaced, especially in the absence of vision. This issue can be tackled with actuated interfaces, defined as "*interfaces in which physical components move in a way that can be detected by the user*" [242]. Actuation can be used to update the physical representation of a TUI by, for example, altering the shape, speed of motion and position of the tangible objects. Therefore, actuation can "preserve consistency between digital and tangible representations" [242]. The earliest examples of actuated tabletop TUIs include PsyBench [19] and the Actuated Workbench [228], which made use respectively of a single electromagnet and an array of electromagnets to move objects above a surface. PsyBench [19] was designed to support remote collaboration with TUIs: if a user moved one object on his/her workspace, then the corresponding object on the other user's workspace could be moved by the system so that both representations remained identical.

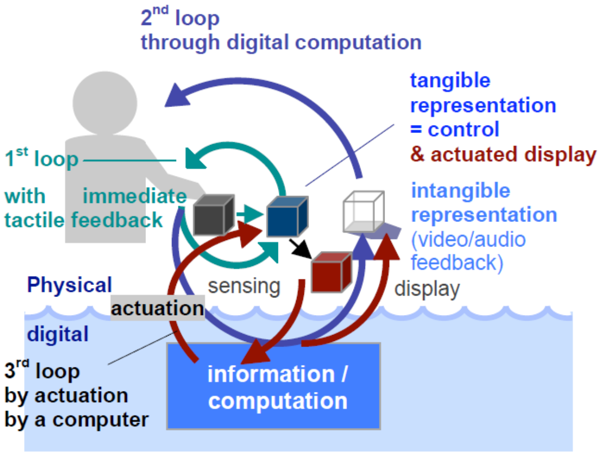

Figure 2.30. The third feedback loop in the MCRit model of TUIs [305]. **(Retrieved from** [111]**).**

Actuation can be integrated into the interaction model proposed by Ullmer and Ishii [305], in addition to the passive haptic feedback loop and to the digital feedback loop (Figure 2.30). This physical actuation loop "allows the computer to give feedback on the status of the digital information as the model changes or responds to internal computation » [111] and can also increase the malleability of tangible objects [242]. Although actuation can be used for a variety of purposes (e.g. making a tangible object vibrate to draw the user's attention), we will focus here on systems where tangible objects can move or can be moved without requiring users' manipulation.

Up to now, most actuated tabletop TUIs can only move a limited number of tangible objects simultaneously. However, with the reduction in size of tangible objects that can move by themselves, it is now possible to envisage displays made up of a large number of tangible "pixels", greatly increasing the complexity of tangible representations. Poupyrev et al. [242] used the term s*elf-rearranging* displays to refer to “devices that consist of multiple parts that can dynamically re-arrange themselves in space”. Based on Zooids, small robots that we later describe in detail, Le Goc et al. [81] introduced the term *Swarm User Interfaces* (SUIs) to designate “human-computer interfaces made of independent self-propelled elements that move collectively and react to user input”. In that sense, SUIs could therefore be seen “as a coarse-grained version of [] futuristic visions of user interfaces based on programmable matter” [81]. As we said in the introduction, although shape displays are very promising they still require complex hardware and set-up. By using small robots it is possible to build physical and dynamic displays that are not as expensive and complex as shape displays and that can be more finely controlled than shape displays based on continuous control (e.g. pneumatic actuation).

4.2 TECHNOLOGIES

Two main approaches exist to move an object over a surface [232,255]: the tangible objects can be moved by the surface itself, or they can move on their own.

4.2.1 ELECTROMAGNETIC SURFACES

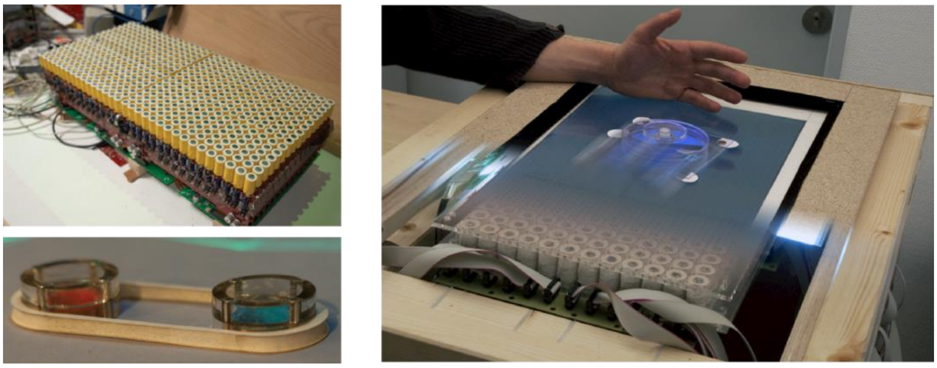

Figure 2.31. Two examples of electromagnetic surfaces. Left: with PICO, users could constrain the movement of the tangible objects (retrieved from [231]**). Right: Madgets (retrieved from** [334]**).**

Tangible objects can be moved by the surface itself, usually composed of a number of electromagnets. Well-known examples include the Actuated Workbench [228], PICO [231] and Madgets [334]. With the PICO [231] system, the use of physical constraints on tabletop TUIs was investigated (Figure 2.31, left). The application enabled users to simulate the placement of telephone towers in order to provide the best telephone coverage. Active tangible objects represented the towers and moved to positions computed by the system based on a set of computational constraints. Users could add and remove towers to visualize the impact on overall coverage, but they could also restrict the movements of the objects using their hands or physical objects (e.g. a rubber band or a ring could be used to enclose two towers while a “collar” placed around a tangible object prevented it from being too close to others, see Figure 2.29, bottom left). As for Madgets [334], they consisted in magnetic widgets that embedded at least four permanent magnets (Figure 2.28, right). An array of magnets was used to control the position and orientation of the tangible objects, but also to activate parts of the widget. For example, the system supported tangential movements (e.g. to move a slider) as well as z- movements (e.g. a radio button could be raised up or down).

4.2.2 Mobile tangible objects

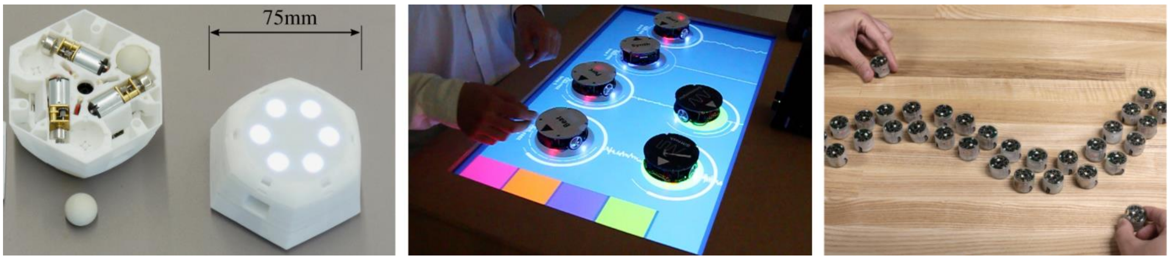

Figure 2.32. Three examples of actuated tabletop TUIs with mobile tangible objects: Cellulos [223]**, Tangible Bots** [232] **and Zooids** [81]**. (Respectively retrieved from [ref],** [232] **and** [81]**.)**

On the other hand, the objects can move by themselves. They are usually motorized custom-made or off-the-shelf robots equipped with two wheels that can be controlled either remotely or by displaying a particular pattern that the robots interpret in order to move, rotate, or change speed. Cellulos, for example, are custom-made robots (around 7.5 cm diameter, see Figure 2.32, left) that are composed of three ferromagnetic balls that are controlled by a PCB embedded into the robots (see [222] for more details) and that were designed to be used for educational purposes. The Tangible Bots [232] developed by Pedersen and Hornbaek were based on commercialized robots (around 10 cm diameter, see Figure 2.32, middle). The authors investigated the design of interaction techniques with the Tangible Bots such as *indirection interaction* techniques that allowed users to move the robots without touching them (e.g. by drawing a path that they must follow) or by controlling several robots at the same time. More recently, Le Goc et al. [81] proposed a new platform composed by many Zooids, which are small (2.6 cm), affordable (50 $) and high-speed (44 cm/s) custom-made robots (Figure 2.32, right). Several scenarios were described: three scenarios described how users could draw predefined shapes, such as circles or rectangles, by using two Zooids that served as “handles”, or how they could draw Bézier curves by manipulating specific Zooids that acted as control points. Zooids could also support interactive visualization, for example to navigate time-series data (some Zooids represented the data points whereas others acted as sliders to filter which data to display) or scatterplots.

4.2.3 Comparison of existing technologies

To sum up, electromagnetic surfaces do not require the objects to be powered, but are expensive and complex to build. In addition, with such technologies the system cannot detect the orientation of the tangible objects unless several magnets are embedded within the object (e.g. [334]), which results in relatively large tangible objects. The main advantage is that the objects can be extremely cheap and relatively small. Also, with such surfaces, tracking the objects with a camera placed below the surface is not possible and therefore either the camera must be placed above the tabletop (which may lead to occlusions) or alternative tracking solutions must be considered (e.g. RFID in [231] or a grid of fiber-optic cables that is similar to the use of a camera in [334]). However, these solutions require additional dedicated and relatively expensive hardware. Mobile-based tabletop TUIs are easier and usually cheaper to build than electromagnetic surfaces. However, the tangible objects must be powered and must embed sensors, making them more expensive and complex to build. Riedenklau [255] also pointed out that “electromagnetic actuation allows to apply force to the [tangible objects] even when they are slightly lifted from the surface by the users", which is not the case with mobile-based surfaces. In all cases, tangible objects that can move or can be moved differ in size, motion speed and motion abilities (holonomic or non-holonomic movements[34]). With the advent of robotics, it is easier and easier to buy or build affordable and small robots with a relatively high motion speed: therefore mobile-based robots appear to be a very promising approach for the design of actuated tabletop TUIs or SUIs.

5 CONCLUSION OF PART D

In this part, we provided an overview of the main theories and characteristics of (tabletop) TUIs. In particular, we introduced the MCRit model [305], which emphasizes the fact that TUIs are built on a digital model that is rendered using both intangible and tangible representations. We also described the taxonomy proposed by Holmquist et al. [102] to describe the different roles of tangible objects: containers, tools and tokens. TUIs have been studied from various perspectives, and throughout the years a number of important characteristics of TUIs have been identified. We presented some of them, along with benefits of TUIs for collaborative, learning and spatial applications. We also described the most widespread technologies for implementing tabletop TUIs. Object tracking can be achieved with internal or external sensing: although internal sensing is very promising, systems based on external sensing are most common, probably due to their simplicity. The most common technology is to place a camera below a tabletop and to track fiducials attached underneath the tangible objects. For finger tracking, a number of solutions exist and can be broadly classified into camera-based technologies and electric-based technologies. Along with traditional approaches (a camera placed below a surface that is illuminated with infrared LEDs), new technologies such as infrared frames and capacitive foils are now available on the market and provide an easy way to implement multitouch surfaces. Finally, we described the field of actuated tabletop TUIs: actuation can be used to preserve consistency between digital and tangible information, but it can also be used to make TUIs more dynamic, and therefore compensate for their limited scalability. We discussed two main approaches for implementing actuated tabletop TUIs (electromagnetic surfaces and mobile-based interfaces), and highlighted the fact that systems based on robots are particularly promising, notably in the context of the development of Swarm User Interfaces. Having described the properties and implementation technologies of tabletop TUIs, we address in the next and last part of this chapter the design of usable interaction techniques, tangible objects and feedback for tabletop tangible maps and diagrams for visually impaired users.

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[34] Holonomic robots can freely move in any direction while non-holonomic robots cannot (they must turn before moving (as cars).

PART E

DESIGNING TABLETOP TANGIBLE MAPS AND DIAGRAMS FOR VISUALLY IMPAIRED USERS

1 INTRODUCTION

Tabletop TUIs for visually impaired users rely on the same technologies as tabletop TUIs for sighted users and may therefore present the same benefits, and, of course, limitations. However, their design must address specific and additional issues as the intangible representation cannot rely solely on visual feedback. In this part we first discuss to what extent the properties of tabletop TUIs for sighted users differ from those for visually impaired users. We then provide a detailed description of eight prototypes of tangible maps and diagrams for visually impaired users and analyze them in relation to four main dimensions: content, design of the tangible objects, interactivity and technology. Based on this analysis, and on existing guidelines, we draw up a list of aspects that appear important when designing tangible maps and diagrams for visually impaired users, and that we will investigate in more detail in the following chapters.

2 SPECIFICITIES OF NON-VISUAL TABLETOP TUIS

If we refer back to the MCRit model [305], the main difference between tabletop TUIs for sighted and visually impaired users is that the second feedback loop cannot rely on the visual modality alone. In fact, where the system is intended to be used by blind users, the visual modality cannot be used at all. From this a number of issues arise.

The first issue is that the representation cannot be as complex as it could be if visual feedback was allowed. For example, in several map prototypes, a limited number of physical building models were used but a large amount of information was displayed visually (shadows, streets, trees, pedestrians' crossings, etc.). Text can also be displayed to convey numerical information. Even though a certain number of pieces of digital information can be rendered with vibrations or sounds, tangible maps and diagrams for visually impaired users can in no way be as complex as tangible maps and diagrams for sighted users. In fact, it is the same limitation that we previously identified when discussing the production of tactile maps and diagrams. Visual content must be adapted, and, in most cases, simplified, to become accessible via the senses of touch and hearing. One way of addressing this issue is to design tangible objects that can be used to represent various and complex digital information. While most prototypes of tabletop TUIs for sighted users rely on circular or square tangible objects (i.e. *points)*, we hypothesize that being able to physically render digital *lines* (and possibly *areas*) could increase the expressiveness and complexity of tangible representations that do not rely on visual feedback. However, increasing the number of tangible objects and/or their expressiveness should not come at the cost of an increasingly tedious exploration. As we will more thoroughly discuss in the next sections, users must be able to explore the tangible representation using their hands and without easily moving the tangible objects, otherwise the representation would become incorrect or the benefits of two-handed exploration would not be relevant anymore.

The second issue is that since the tangible representation cannot be augmented by visual feedback, users cannot immediately understand what the tangible objects represent or can be used for. On the contrary, using visual feedback, it is possible to project onto or display under the tangible objects colors, labels, shapes, etc. In particular, visual feedback allows users to easily distinguish between two tangible objects that share similar physical properties (size, texture) but around which different colors/labels are displayed. More generally, visual feedback provides users with a sense of *embodiment* and helps them understand that they can explore and manipulate the digital representation by manipulating the tangible objects. Therefore, the design of tangible objects for visually impaired users must be adapted (so that each tangible object can be easily identified) and/or interaction techniques must be provided to help users understand what a tangible object either stands or can be used for.

When interacting with a tabletop TUI, sighted users can very quickly position the tangible objects in their right place if required (e.g. by placing two buildings on a street). Once again, visual feedback can be used to indicate where an object must be placed, or in which area it must be manipulated to trigger a particular command. In the absence of visual feedback, suitable interaction techniques must be provided to help visually impaired users place the tangible objects in their right place, so that they can later explore and possibly edit the representation. Similarly, if one tangible object is incorrectly placed, leading to inconsistencies between the digital and the tangible representation, sighted users can quickly notice it and replace it. Such a situation can be more problematic if the users cannot see that an object has been misplaced; if the system warns them, feedback must be precise enough to help the users relocate the object. In all cases, feedback appears to be particularly important in the design of tabletop TUIs for visually impaired users.

The reliability of the technologies used is also very important. In particular, if objects are not properly tracked, users may not be able to understand why the system is no longer responding. For example, placing a camera above the surface to track objects and/or fingers may result in occlusions that the user is not aware of. On the contrary, using visual feedback, it can be very easy to indicate whether a tangible object is active or not. As for finger tracking, multitouch surfaces may cause issues when used by visually impaired users as unintentional inputs are often triggered [24]. Since one of the main advantages of TUIs for visually impaired users is the fact that they support two-handed exploration, users should be confident in using both hands without being afraid to involuntary trigger audio feedback.

Another aspect that would be worth investigating, but that we are unable to in this thesis, is the question of collaboration[35]. In Part C, we indicated that one benefit of TUIs lies in their collaborative use, and particularly in the fact that they provide a sense of *awareness* that is essential to enable users to work together. However, this sense of *awareness* is mainly based on the fact that users are able to see what the other users are doing, which objects they are manipulating, and how. In the absence of vision, providing a similar sense of *awareness* is a design challenge that has rarely been addressed in the literature (although see [108,300]. It also raises the question of the

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[35] See Chapter 6, 4.2 for a discussion on collaborative TUIs for visually impaired users and a description of two ongoing projects.

relevance of audio feedback in a collaborative context: when several users are interacting simultaneously, how to provide understandable audio feedback to each of them?

To sum up, tabletop TUIs for visually impaired users present the limitations inherent in every tabletop TUIs (see Part C), but they also present additional limitations that must be overcome as much as possible. In particular, the content of tangible maps and diagrams for visually impaired users cannot be as complex as that for sighted users; the tangible objects must be carefully designed; suitable interaction techniques must be designed to enable users to explore and reconfigure the representation; technologies should be carefully chosen to provide reliable finger and object tracking while preventing occlusions and/or unintentional selections. In the next section we will review a number of prototypes and solutions that have been proposed to address these limitations.

3 DESCRIPTION OF EXISTING PROTOTYPES

As we already mentioned, the number of projects relative to the development of tangible maps and diagrams for visually impaired users is limited. Besides, existing projects have not always resulted in implemented and/or evaluated prototypes. Nevertheless, even incomplete projects may reveal interesting questions about the design of non-visual tabletop TUIs. In this section, we describe in detail existing prototypes or design ideas in order to identify issues encountered or discussed by the authors, as well as solutions that have been proposed. As each prototype was explicitly intended to support the (re)construction and/or exploration of maps *or* diagrams, we present them in two categories: tangible maps and tangible diagrams.

3.1 MAPS

The **Tangible Pathfinder** [278] was designed to be independently used by a visually impaired student during Orientation & Mobility lessons. Although to our knowledge it was not implemented, the authors envisaged that a tangible map or itinerary could be represented on a tablet thanks to a set of small-scale tangible objects that could represent elements that are important for navigation (sidewalks, walls, pedestrian crossings, etc.), and that would be tracked by the tablet. The corresponding digital model could be downloaded from an online database by the students themselves. Three activities were envisaged: the prototype could be used as a static tactile map; the map could be explored in an interactive manner by moving a tangible avatar above the tablet and 3D audio feedback would be given accordingly; the prototype could serve as a self-assessment tool, allowing students to reconstruct the map or itinerary from memory while receiving feedback about the accuracy of the reconstruction. The authors also mentioned that the tangible objects could “speak” in order to provide the user with pieces of information about the point of interest that they represent. Finally, the authors envisaged that “given sufficient miniaturization the Tangible Pathfinder could be used as a portable, autonomous [Orientation & Mobility] guide” that users could carry with them when walking.

The prototype proposed by Schneider and Strothotte, which we will refer to as **Tangible Itinerary** [272], was based on a similar idea. The aim of the authors was to foster the active participation of the students when learning a new route by letting them independently construct an itinerary. A set of objects of varying lengths representing route segments were placed next to the user, who was then guided by the system to place them in their right place. A tactile grid was used to indicate the working area and a camera was placed above the table to detect the position of the building blocks and one of the user's fingers, marked with a colored ring. In the exploration mode, users could explore the digital map as well as the tangible itinerary by moving their tracked finger above the surface: verbal descriptions and sounds were given accordingly. In the construction mode, audio instructions were given to help users construct the itinerary. First, the system told the user the length of the next object to be placed. Once the user had placed the object next to the previous one, the system indicated the orientation of the route segment. The procedure was repeated until the whole itinerary had been reconstructed. Users could switch from the exploration to the construction mode by placing two tangible route end blocks at the beginning and end of the itinerary; the system therefore computed the shortest path. To make the itinerary more stable, magnets were placed at the extremity of each route segment so that two adjacent bricks could be connected. The authors also mentioned that the objects were designed "in a way that they [could] be held in the middle while still leaving the top unoccluded". They also indicated that a "metal pad" was used to prevent the tangible objects from being moved accidentally. One blind user was able to construct an itinerary composed of five route segments and had "fun" interacting with the system. Interestingly, all graphical information was displayed on the computer to support cooperation between a sighted and a blind user.

3.2 DIAGRAMS

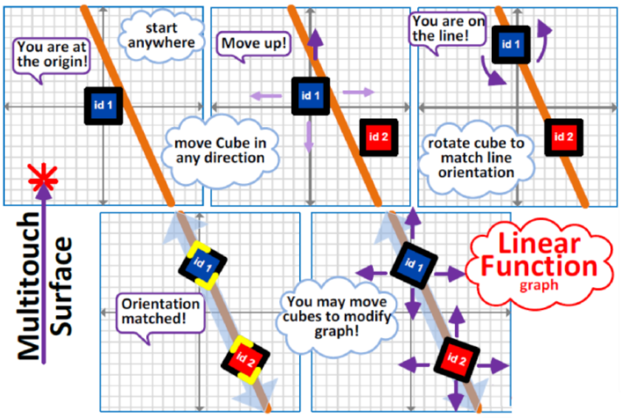

Figure 2.33. Construction of a line graph with the Trackable Interactive Multimodal Manipulatives (retrieved from [182]).

TIMM (Trackable Interactive Multimodal Manipulatives) [181,182] were interactive tangible objects that provided multimodal feedback such as sounds and vibrations for the autonomous exploration, creation and edition of diagrams by visually impaired users (Figure 2.33). A number of interaction techniques and functionalities were proposed but the authors did not indicate how users could switch between modes and how the interaction techniques and functionalities could be adapted for the different types of diagrams mentioned (line graphs, UML diagrams, drawings of molecular structures, etc.). In addition, it is unclear whether the TIMM were implemented as no evaluation was conducted. To reconstruct a diagram, two techniques were proposed. First, users could explore the tabletop with their hands until they heard a sound indicating that they had found an element: they could then place a TIMM in that position. Alternatively, they could be guided by audio instructions (e.g. "go left") to place the TIMM in its right place. The authors suggested that a tactile line could be added between two TIMMs using a piece of yarn or a wooden stick. To create a graph users could place several TIMM on the tabletop and were "then asked to describe or provide a description using a standard or a braille keyboard". To edit a diagram, users could interact with the system with multitouch gestures. Otherwise, they needed to correctly orientate the TIMM: "If the orientation and position of a TIMM matches a component, then a user is allowed to modify that component by moving the TIMM". During the edition of a graph audio feedback was provided (e.g. "the slope of the line is now negative"). The authors also mentioned that the "representation could be saved and printed". In another publication [180], the use of TIMM for remote collaboration was discussed. For example, the authors envisaged that a teacher could remotely check whether his/her students were able to correctly construct a line graph. Finally, the authors indicated that visual feedback had to be provided to support collaboration between blind and sighted users.

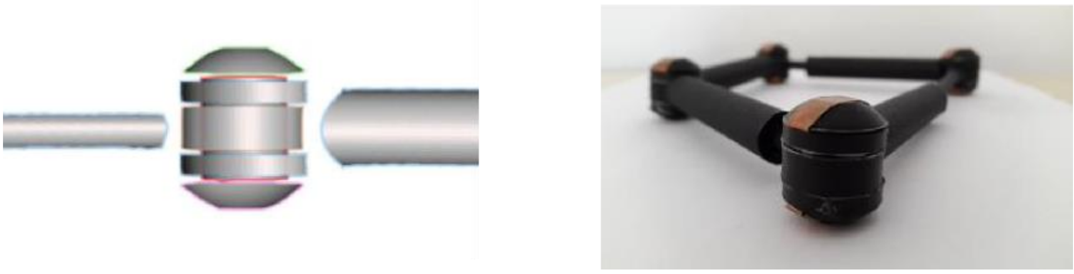

Figure 2.34. The Invisible Tangible Geometry prototype. Each object is composed of a node and two edges (one narrow rod and one wide rod). Retrieved from [261].

The **Invisible Tangible Geometry** [261] prototype combined an Android application with a tangible *appcessory* and aimed to help visually impaired users learn geometry (Figure 2.34). In the draw mode, users could indicate points on the tablet by touching it. The application therefore computed the corresponding shape (e.g. indicating three points resulted in drawing a triangle). The digital shape could then be explored: touching the lines resulted in vibrations and two different sounds were played when the user touched the inside or the outside of the shape. As for the *appcessory*, it consisted in a set of 3D-printed objects that could be assembled together to create a tangible representation of the digital shape. Each object was composed of a *node* (a cylinder surrounded by three rings that could rotate around it) and two *edges* (one narrow rod and one wide rod), as shown in Figure 2.34, left. The two edges could be rotated around the node and shapes could be assembled by inserting the narrow rod of one component inside the wide rod of another component. Therefore, it was possible to adjust the length of each edge. The nodes were designed so as they could be placed on the tabletop whereas the rods were slightly raised. In addition, the nodes were covered with copper so that users could interact with the tablet by touching them. Users could create a physical shape and then touch each node to enable the application to create the corresponding digital shape. This prototype was presented to three visually impaired people. Although a number of comments were made concerning the exploration of the digital shapes, we only report comments made about the *appcessory*. Participants found it "too flexible and not robust enough", which made them feel nervous and uncomfortable. The authors also reported that during the evaluation one rod detached from its node and suggested that it would be necessary to "increase the strength and stability of the rod" in order to make them "more stable but less flexible".

Jafri et al.'s prototype, which we will refer to as **Tangible Shapes** [119]**,** aimed to teach tactual shape perception and spatial sub-concepts such as orientation to visually impaired children (Figure 2.35). The principle was to provide children with 3D-printed objects (e.g. a cube, a pyramid) with a fiducial marker on each face. A camera was placed below a transparent surface where the objects could be placed. A number of scenarios were proposed. We describe some of them: 1) when an object is detected, its name is given (e.g. "pyramid"); 2) when an object is detected, the system asks the student to give its name and feedback is provided to indicate whether the answer is correct or not; 3) the student is asked to turn the shape on its right side or upside down and feedback is given to help the student correctly perform the task; 4) the student is asked to place an object next to/to the right of another object, and the relative positions of the objects are checked by the system.

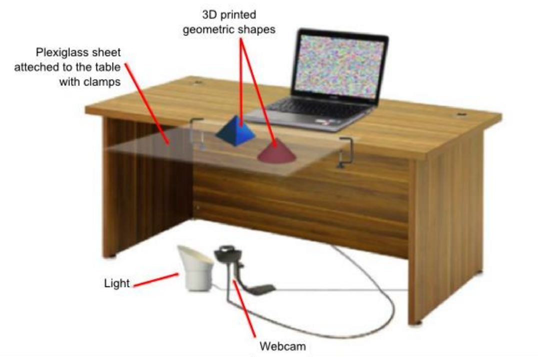

Figure 2.35. Jafri et al.'s prototype, referred to as Tangible Shapes. Retrieved from [119]**.**

The **Digitizer Auditory Graph** [36]**,** which we already described in Part C, 4.2, enabled users to create line graphs using Wikki Sticks (Figure 2.36, left). The constructed graph was captured by a camera placed above the surface in order to create a sonified version of the graph. Four visually impaired users and four sighted users were asked to create four graphs and to listen to their sonified versions. The visually impaired users found the system predictable, responsive and had a good overall experience. All comments reported in the article concerned only the sonification of the graph.

The **Interactive Auditory Scatter plot** [256] used actuated tangible objects to make scatter plots accessible to visually impaired users (Figure 2.36, right). A TAO is a mobile robot that could be tracked by a camera placed below a transparent tabletop. Clusters of data points were identified and the tangible objects moved to the cluster centers, allowing users to have a rough idea of how the data is organized. When moving an object, feedback was provided with sonification techniques to give a more precise description of the structure of the data points under the object. In a first user study, nine blindfolded participants were asked to explore a scatterplot and then to identify it among three datasets. Around 70% of the participants managed to recognize the explored dataset. Some remarks were made about the use of the prototype: one participant found it very easy to locate an object; several used the frame surrounding the surface to estimate distances between clusters or data points.

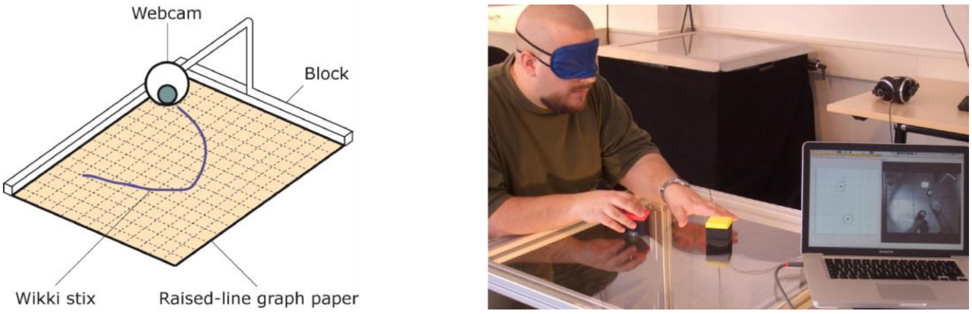

Figure 2.36. Left: the Digitizer Auditory Graph. Right: the Interactive Auditory Scatter plot. (Respectively retrieved from [36] **and** [256]**.)**

The **Tangible Graph Builder** [196] allowed the exploration of line graphs and bar charts (Figure 2.37). The tangible objects had to be placed within a physical grid made out of straws and could represent the top of a bar (for bar charts) or the turning points of a linear function (for line graphs). For the line graphs, two different shapes were used (a cube and a cone) to represent two data series (see Figure 2.37, right). Cubes were filled with plasticine so as to be heavier than the polystyrene cones. In both cases a fiducial marker was fixed under the tangible objects, which were tracked by a camera placed below a transparent tabletop. No interaction techniques were designed for the construction of the graph. For the exploration a *sonification strip* was placed under the x-axis: a particular tangible object could be moved within this strip and different sounds were played to convey the corresponding y-value. For the line graphs, users could choose which data series had to be sonified by placing a cube or a cone within a *control area* placed along the y-axis.

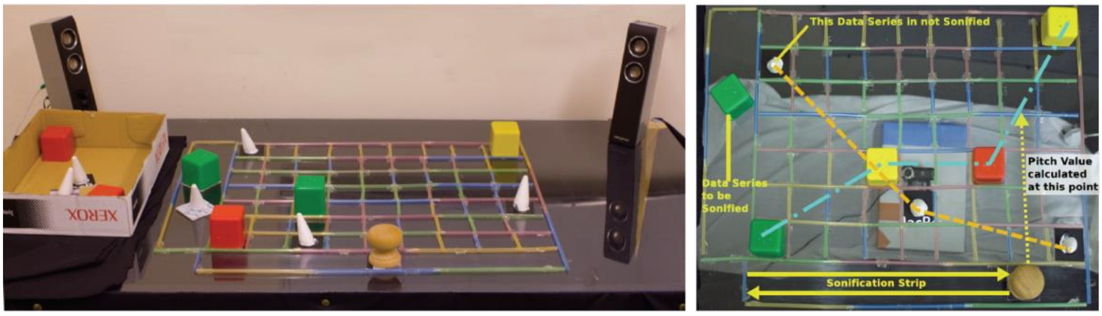

Figure 2.37. The Tangible Graph Builder allowed the exploration of line graphs and bar charts. Retrieved from [196].

A first evaluation was conducted with eight blindfolded participants who had to construct line graphs with two data series and bar charts, based on a printed table containing the data points to be represented. They also had to browse line graphs and bar charts to answer questions such as finding the three highest bars. Concerning the design of the tangible objects, seven participants preferred the cubes over the cones, mainly because they found the cubes less easy to knock over: nine cones and one cube were dislodged during the evaluations, which sometimes resulted in participants replacing the tangible objects in the wrong cell or placing the cubes upside down. Issues also arose due to the unreliable tracking of the fiducial markers and particularly of the tangible object used within the sonification strip. This resulted in participants expressing “their lack of confidence in the sonification”. A similar study was conducted with four blind participants and similar issues were reported. The notion of “division of functionality” was also discussed.

Based on a previous work [34], the authors made the distinction between three types of data: data that are fixed, which must be rendered with objects that cannot be moved (e.g. the tangible grid); data that are frequently and directly changed by the user, which must be rendered with objects that can be moved (e.g. the height of each bar was represented by a tangible object); data that are frequently and indirectly changed by the user, which must be rendered with intangible representations (e.g. relationships between data points were rendered by sounds). The authors concluded by providing four guidelines: 1) tangible objects should be physically stable; 2) tangible objects should have irregular forms (to ensure that the fiducial marker is always placed against the tabletop); 3) functionality should be appropriately divided; 4) participants should be aware of the tangible objects' status (e.g. when a tangible object is misplaced or is not detected by the system).

4 ANALYSIS OF EXISTING PROTOTYPES

In this section, we provide a summary and analysis of the different prototypes of tangible maps and diagrams that have been designed for visually impaired users.

4.1 OVERALL CHARACTERISTICS

We identified two prototypes of tangible maps (Tangible Pathfinder and Tangible Itinerary) and six prototypes of tangible diagrams (TIMM, Invisible Tangible Geometry, Tangible Shapes, Digitizer Auditory Graph, Interactive Audio Scatter plots, Tangible Graph Builder). Among these prototypes the Tangible Pathfinder was not implemented and the TIMM, the Tangible Shapes, the Digitizer Auditory Graph and the Invisible Tangible Geometry were described as being under development. At the time of writing, there were no other publications suggesting that these prototypes had been fully implemented. As the last publication concerning the TIMM was in 2013 and the only publication concerning the Digitizer Auditory Graph was in 2010, it seems very likely that the development of these two projects has been discontinued. Except the Tangible Graph Builder, none of the prototypes have been formally evaluated with visually impaired users; informal user studies were conducted with very few visually impaired participants and/or with blindfolded participants. All prototypes were designed for a single user. However, in the latest publication concerning the TIMM, the authors discussed how their system could be used for remote collaboration between one sighted teacher and one or several visually impaired students.

4.2 CONTENT: NATURE, COMPLEXITY AND "BI-GRAPHISM"

Concerning the **nature and complexity** of the tangible representations, the prototypes of tangible maps were designed to support the construction of Orientation & Mobility (the Tangible Pathfinder) or of itineraries (Tangible Itinerary). Since the first was not developed it is unclear how complex the maps would be. As for the Tangible Itinerary, the evaluation showed that one participant was able to construct itineraries composed of five route segments.

The prototypes of tangible diagrams were designed to support the construction or exploration of simple geometrical shapes (Invisible Tangible Geometry and Tangible Shapes), graphs of a function (Digitizer Auditory graph), scatter plots (Interactive Audio Scatter plots) and line graphs composed of two data series and bar charts (Tangible Graph Builder). Since the Tangible Graph Builder relied on a 9 * 7 tangible grid, up to nine bars could be constructed. As for the Interactive Audio Scatter plots, the tangible objects only represented clusters of data points (and not data points): during the evaluations, participants had to explore scatterplots composed of three clusters. TIMM was designed to support the construction of various diagrams, including line graphs, UML diagrams and drawings of molecular structures. However, it was under development at the time of publication and it is unclear whether a working version of the prototype would have supported the construction of all these types of diagrams.

In terms of **bi-graphism**, apart from the Invisible Tangible Geometry prototype, which displayed the digital shapes on the tablet in addition to the tangible shapes, none of the prototypes displayed a visual representation under the tangible representation. The main reason is that most prototypes relied on a transparent tabletop under which a camera was placed to track the objects and that no projector was used. However, the importance of having a visual representation to enable collaboration between sighted and visually impaired users was pointed out by the authors of Tangible Itinerary (who displayed the map on a computer) and TIMM. Nevertheless, all tangible representations were visible and understandable by a sighted person.

4.3 TANGIBLE OBJECTS

In terms of possible ***implantations***, tangible objects were most often used to represent points or clusters of points (TIMM, Interactive Audio Scatter plots and Tangible Graph Builder). The Digitizer Auditory Graph relied on tangible lines that were built with Wikki Sticks while the Tangible Itinerary prototype relied on rectangular tangible objects of varying lengths. The Invisible Tangible Geometry was the only prototype to support the construction of length-adjustable lines. This could be done by inserting narrow rods inside wide rods. However, participants reported that these tangible objects were too flexible. During the exploration of the shapes built with this prototype, different sounds were played depending on the position of the finger – inside or outside the shape. This was the only prototype to support the exploration of areas, but the areas were not, strictly speaking, physical. Finally, the authors of TIMMs mentioned the use of Wikki Sticks or wooden sticks to create lines between two TIMMs.

In terms of **shape***,* two types of tangible object were designed for the Tangible Graph Builder: cubes and cones. Since participants sometimes placed the cube upside down, the authors suggested that tangible objects should have irregular forms. In Tangible Itinerary, the authors said that the tangible objects were designed so that users could handle them without obstructing the camera's view, but no description of the objects was provided.

One essential aspect of tangible objects is their **stability**. In Tangible Itinerary, magnets were placed at the extremity of each rectangular tangible object in order to make the whole structure more stable. In addition, a "metal pad" was used, probably to keep the objects in place. In the Invisible Tangible Geometry prototype, participants reported that the whole shape was not stable enough and that increasing the stability of the rods was necessary. During the evaluation of the Tangible Graph Builder, several objects were knocked over, despite the fact that a physical grid was used. The cubes, which were heavier than the cones, were in fact preferred by the participants because they were more stable. The authors of the Interactive Audio Scatter plots did not mention any issue with the stability of the tangible objects; however, there were only three objects placed on the table and the objects were able to autonomously return to their anchor position after they had been moved by the users.

It is worth discussing whether the prototypes ensured a strong **coupling** between the physical and digital components of the interface. All tangible objects that represented points were tracked; however, tangible lines were not always coupled with a digital line. For example, in TIMM, a tactile line could be added between two objects but the authors did not indicate whether the system could detect whenever a tangible line was constructed so as to update the digital model. On the contrary, in the Invisible Tangible Geometry prototype, users could construct a tangible shape and then, by clicking on the nodes, create the corresponding digital shape. However, it seems that users could only interact with the tangible nodes, not with the tangible edges.

Apart from the Interactive Audio Scatter plots and TIMM prototypes, the **actuation** of the tangible objects was not considered. With the Interactive Audio Scatter plots, tangible objects were mobile and could move towards the center of clusters of data points. As for TIMM, the authors mentioned that they could embed sensors and actuators that would provide three interaction techniques: *rolling* would enable the system to detect which face of the TIMM is against the tabletop (e.g. to simulate a dice); *stacking* would enable each TIMM to be aware of any TIMM stacked upon it; with the *guide* feature users would be allowed to plug a tactile arrow on top of a TIMM, which could be rotated by the user or by the TIMM itself to indicate a direction (e.g. the slope of a line on a line graph). The authors of the Tangible Pathfinder also mentioned that the tangible objects could "speak" and that they could vibrate to provide additional feedback.

Finally, most tangible objects were **tokens** and very few were **tools**. In most prototypes, the tangible objects were used to make the digital representation tangible. However, with the Tangible Graph Builder, one object could be used as a sonification tool and objects that were placed within the control area (to choose which data series to display) were also used as tools. With the Interactive Audio Scatter plots prototype, the tangible objects represented cluster centers (tokens) but could also be moved by the user to trigger feedback about the underlying data points (tools).

4.4 INTERACTIVITY

We identified four main functionalities: constructing or drawing a representation, reconstructing a tangible representation from an existing model, editing/annotating a representation, and exploring a representation. For each of these functionalities, several interaction techniques were proposed but these were rarely evaluated.

Three prototypes enabled the **construction** of a tangible representation without a model. With the Digitizer Auditory Graph, users had to construct the graph of a function using Wikki Sticks and then capture its image with a camera, and the system would thereafter sonify the graph. With the Invisible Tangible Geometry prototype, users could construct a shape using tangible objects and then click on each node to create the digital model. Finally, with the TIMM prototype, users could place tangible objects on the surface and provide a description of each object with a standard or Braille keyboard.

Four prototypes enabled the **reconstruction** of an existing (digital) representation but the Tangible Pathfinder and the Tangible Graph Builder did not provide interaction techniques for guiding the user during the reconstruction of the map or diagram. A technique based on audio feedback was described for the Tangible Itinerary prototype but only supported the construction of route segments. Besides, this technique was evaluated with one user and for only five route segments. As for the TIMM prototype, users could either be guided by vocal instructions or use their hands to explore the tabletop and find the position of the elements of the representation, but these techniques were not described in detail and were not evaluated. With the Tangible Shapes prototype, some learning activities required the students to follow vocal instructions to place the tangible objects in a particular position.

Only the authors of TIMM considered the **edition** of a line graph. They suggested that the tangible object had to match the orientation of the line graph in order to activate the edition mode. Then, as the tangible object was being moved, audio feedback was provided to indicate changes such as switching from a positive to a negative slope. To our knowledge, this technique was not implemented.

For the **exploration** of the tangible representations two main techniques were proposed: finger-based exploration (Tangible Itinerary, TIMM) or tangible-based exploration (Tangible Pathfinder, Tangible Shapes, Interactive Audio Scatter plots and Tangible Graph Builder). With the Digitizer Auditory Graph prototype users could only listen to the sonified graph. With the first approach (finger-based exploration), it is unclear whether users could retrieve a piece of information on demand or if feedback was continuously provided. Besides, the TIMM's authors did not indicate how they would track only one finger to avoid unintentional selections. With the second approach, users could move a tangible avatar above a map (Tangible Pathfinder), place an object within the camera's field of view to retrieve its name (Tangible Shapes) or move tangible objects to trigger audio feedback based on sonification technique (Interactive Audio Scatter plots and Tangible Graph Builder). In these cases, users could not select a particular point to retrieve its value.

Various types of **feedback** were proposed and were mainly used during the (re)construction or exploration of the map or diagram. Verbal instructions, musical notes and spatialized sounds were considered. Three prototypes of tangible diagrams relied on sonification techniques (Interactive Audio Scatter plots, Tangible Graph Builder and Digitizer Auditory Graph). Interestingly, the authors of the Tangible Graph Builder recommended providing feedback concerning the status of the tangible objects, for example when they are not properly detected by the system or when they are incorrectly placed.

In fact, McGookin and Brewster [192] investigated how and in which cases tangible objects could provide feedback. Following a brainstorming with a blind usability expert, they proposed three aspects to consider when designing tangible objects for visually impaired users. Firstly, both static (e.g. texture) and dynamic (e.g. lights and vibrations) properties should be considered, dynamic properties being particularly beneficial as they are more flexible. Secondly, feedback could be provided for different types of interaction: interrogation + response (e.g. when the user touches the tangible object, speech output is provided); attracting attention (e.g. the tangible object can vibrate or emit a sound alert when the object is incorrectly placed); localization + homing (the use of a fan that could blow air out of the tangible objects was suggested to help users quickly locate the objects by moving their hands above the surface and feeling the air being blown out). Thirdly, different modalities and sensors can be used, as far as possible, to detect when the user touches a tangible object or when his/her hand is close to it.

4.5 AVAILABILITY

In terms of **technology**, two prototypes relied on the use of a tablet (Tangible Pathfinder and Invisible Tangible Geometry). As the Tangible Pathfinder was not developed we do not know how the objects were supposed to be tracked and identified. In the Invisible Tangible Geometry prototype the tangible objects are not tracked but the nodes are composed of copper tape: therefore when the user touched them the tablet could detect their position (but could not identify them). The Tangible Itinerary used a camera placed above the surface to track both the tangible objects and one of the user's fingers (marked by a colored ring). The authors reported that training was required to learn how not to hide the objects from the camera while holding them. The other prototypes were composed of a transparent tabletop, a camera placed below the tabletop and tangible objects with fiducial markers.

For these last prototypes, because no visual feedback was projected onto the tabletop, no projector was required and these prototypes were all very low-cost. The Interactive Audio Scatter plots made use of actuated tangible objects, which may have increased the cost but was still probably affordable. As for the other prototypes, they relied on tablets – a type of device that is extremely widespread and relatively affordable.

4.6 SUMMARY

Table 2.3 summarizes the main characteristics of the existing prototypes. Overall, although several interaction techniques have been proposed for the (re)construction, edition and exploration of tangible maps and diagrams, very few were implemented and evaluated. In particular, the only interaction technique designed for the reconstruction of tangible representations only supported the construction of a single route composed of a sequence of building bricks. Concerning the design of the tangible objects, their stability appeared to be essential but this aspect was explicitly considered for only two prototypes (Tangible Itinerary and Tangible Graph Builder). The proposed solutions were not entirely satisfying: with the Tangible Itinerary, the "metal pad" required the camera to be placed above the surface, which may lead to occlusions; with the Tangible Graph Builder, the use of a physical grid was not sufficient to keep the objects in place. In addition, the use of a grid prevented the construction of tangible representations that are less structured than graphs or charts. Several prototypes aimed at the construction of tangible lines but the solutions proposed were not satisfying either: the TIMMs did not support the construction of length-adjustable lines; the material used for the Invisible Tangible Geometry prototype, although it allowed the construction of length-adjustable lines, was not robust enough; with the Tangible Itinerary, it is unclear how practical the use of building blocks of various lengths would be for the construction of several lines. The use of actuated tangible objects, although considered in the design of TIMM, was only implemented for the Interactive Audio Scatter plots and lead to interesting interaction techniques and results.

Table 2.3. Summary of the main characteristics of existing prototypes of tangible maps and diagrams in terms of content; tangible objects; interaction; availability. Orange columns indicate prototypes that have never been evaluated or implemented; grey columns indicate prototypes that were under development at the time of publication (work in progress) and that were only partially evaluated by visually impaired (VI), blindfolded (BF) or sighted (S) participants; green columns indicate prototypes that were formally evaluated. Question marks indicate that the corresponding piece of information was not given in the article, most likely because the prototypes were not implemented.

	Name	Tangible Pathfinder	TIMM[36]	Tangible Shape	Invisible Tangible Geometry	Digitizer Auditory Graph	Tangible Itinerary	Interactive Audio Scatterplot	Tangible Graph Builder
General	**Year**	2004	1997	2015	2016	2010	2000	2010	2010
	Working?	No	Under dev.	Under dev.	Under dev.	Under dev.	Yes	Yes	Yes
	Evaluation	No	No	No	2 VI / 2 VI 3 VI	4 Sighted 4 VI	1 BF 1 VI	9 BF	8 BF 4 VI
Content	**Nature**	O&M maps	Graphs, UML, etc.	Volumes	Geometrical shapes	Function graphs	Itineraries	Scatter plots	Line graphs Bar charts
	Complexity	?	?	Cube, pyramid, …	Triangle, squares, …	One line	Up to 5 segments	Up to three clusters	2 lines Up to 9 bars
	Visual feedback	No	No	No	Yes	No	Different surface	No	No
Tangible objects	***Implantations***	?	Points	-[37]	Lines of varying length	Single line	Single line	Points	Points
	Shape	Small-scale models	Cubes	Cube, pyramid, …	Cylinders and rods	Strings	Rectangular and flat	Cubes	Irregular forms
	Stability	?	?	?	?	Wikki sticks	Metal pad Magnets	Mobile objects	Physical grid Weighted cubes
	Actuation	No	Yes	No	No	No	No	Yes	No
	Coupling	?	Not always	Yes	Yes	-	Yes	One object = multiple data points	Yes
	Tokens / Tools	Tokens	Tokens	Tokens	Tokens	Tokens	Tokens	Tokens and tools	Tokens or tools
Interactivity	**Interaction techniques**	Reconst. Exploration	Cons. Recons. Edition Exploration	Recons. Exploration	Cons. Exploration	Cons.	Recons. Exploration	Recons. (by the system) Exploration	Cons. Exploration
	Feedback	Verbal 3D sounds	Verbal Sounds Vibrations	Verbal Sounds	Verbal Sounds Vibrations	Sonification	Verbal Sounds	Sonification	Sonification
Availability	**Technology**[38]	Tablet	Tabletop Below Fiducials	Tabletop Below Fiducials	Tablet Conductive objects	Tabletop Above Shape detection	Tabletop Above Shape detection	Tabletop Below Fiducials	Tabletop Below Fiducials
	Cost	Affordable	Affordable	Affordable	Affordable	Affordable	Affordable	Affordable	Affordable

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[36] The development of this prototype has probably been discontinued.

[37] The Tangible Shapes prototype did not aim at making 2D digital representation tangible. It was a tool to help students retrieve the names of 3D shapes (cubes, pyramids) and therefore the notion of "*implantation*" is not relevant for this prototype.

[38] Below/Above indicate that the camera used to track the objects was placed below/above the surface.

5 DESIGN CONSIDERATIONS AND RESEARCH GAPS

Based on the analysis of the existing prototypes and on existing guidelines, we propose a list of design considerations that should be taken into account, as much as possible, when designing tangible maps and diagrams for visually impaired users:

- Concerning the **content**:
    - Prototypes should support various types of representations.
    - Prototypes should support representations of varying complexities.
    - Points, lines and areas should be rendered, possibly physically.
    - Additional visual feedback should be provided to support collaboration between sighted and visually impaired users.
- Concerning the **tangible objects**:
    - Tangible objects should have irregular forms [196].
    - The elements of the tangible representations should be stable [196].
    - All tangible objects should be coupled with digital information (elements of the representation or functionality).
    - Tangible objects could be actuated to provide additional feedback or functionalities.
    - The conception of “division of functionality” should be considered to decide for which data tangible objects are required and whether they need to be manipulated or not [196].
- Concerning the **interactivity** of the prototypes:
    - Different tasks can/should be considered: constructing a representation from scratch; reconstructing a representation from a digital model; editing an existing representation, etc.
    - Users should be able to easily switch from one mode to another.
    - Users should be able to explore the representation in an interactive manner / the system should know whenever an object is touched or is about to be touched.
    - Different types of feedback should be considered: verbal instructions, 3D sounds, vibrations, etc.
    - Feedback should be provided to help the user be aware of the tangible objects’ status [196].
    - Feedback should be provided to help the user locate a tangible object.
- Concerning the **technologies** used:
    - When a camera is placed above the tabletop, tangible objects should be designed to facilitate objects’ tracking and avoid occlusions.
    - Technologies should be low-cost / affordable.
    - When finger-based interactions are used, one of the user’s fingers should be tracked to avoid unintentional selections triggered by the other fingers.

Obviously, this list is not exhaustive due to the lack of research concerning the design and implementation of tangible maps and diagrams for visually impaired users. As we said in Chapter 1, there is a need to further investigate to what extent tabletop TUIs can be used to make digital maps and diagrams accessible for visually impaired users, both in terms of content and supported tasks. The above list highlights the fact that to answer this question, specific tangible objects, interaction techniques and feedback must be designed and evaluated to support some (if not all) of the above-mentioned considerations. Solutions that have thus far been proposed and evaluated are not fully satisfying and some aspects have not been adequately considered. In the following chapters we propose three prototypes of tabletop TUIs for visually impaired users based on non-actuated and actuated tangible objects, and for which we designed, implemented and evaluated various interaction techniques that supported different tasks.

6 CONCLUSION OF PART E

In this part we first discussed which properties of tabletop TUIs for sighted users could apply to or differ from tabletop TUIs for visually impaired users. In particular, tangible maps and diagrams can probably not attain the complexity of tangible and visual maps and diagrams because they cannot rely on visual feedback. However, we highlighted the fact that designing expressive tangible objects could be a way to compensate for this limitation. We also highlighted the importance of designing suitable interaction techniques and feedback to help users preserve consistencies between the tangible and the digital representations and to help them understand what the tangible objects stand for or can be used for. Based on four main dimensions (content, tangible objects, interactivity and technology), we then describe and analyze eight prototypes of tangible maps and diagrams for visually impaired users and draw up a list of general design considerations. From this analysis we observed that overall only two prototypes have been fully implemented, and among these two, only one has been formally evaluated with visually impaired users. Such an absence of results has led to a lack of knowledge about the usability of the proposed interaction techniques for the (re)construction, edition and exploration of tabletop tangible maps and diagrams, as well as about the proposed solutions for the design of tangible objects, notably in terms of stability and expressivity (i.e. what the tangible objects stand for). It is also unclear to what extent the design of tangible objects, interaction techniques and feedback can compensate for the fact that the intangible representation cannot solely rely on visual feedback (or, in other words, how complex tangible maps and diagrams can be), and which tasks can actually be supported by tangible maps and diagrams in the absence of vision.

Conclusion of Chapter 2

In this chapter, we described the conceptual foundations of this thesis by covering the following aspects:

1. the **benefits of maps and diagrams**, which, as external representations, can notably help users acquire spatial knowledge, identify patterns in thematic maps and reflect upon and solve problems;
2. the **current state of accessibility** of maps and diagrams for visually impaired users, which is mainly restricted by the unavailability of adapted content and the non-interactivity of tactile graphics;
3. the **different approaches that have been explored by researchers** to improve the accessibility of interactive maps and diagrams, and which can be classified into two categories: *digital* prototypes, which most commonly provide a single point of contact, as they cannot be directly "touched": *hybrid* prototypes, which provide multiple points of contact but either suffer from a lack of (or at least a limited) updatability (e.g. interactive tactile maps and maps that are 3D-printed based on users' inputs) or are very expensive (e.g. raised-pin displays);
4. the **core properties of (actuated) Tangible User Interfaces**, which are mainly defined by their physicality - the user can "touch" the tangible objects that embody digital information, be it a piece of information, such as a point of interest in a map (i.e., a *token)*, or a digital operation, such as the scale of a map (i.e., a *tool*) -, and their reconfigurability (the user or the system can "manipulate" the tangible object), as well as the various **technologies** that exist to implement non-actuated and actuated tabletop TUIs;
5. the **challenges that need to be addressed** when designing tangible maps and diagrams for visually impaired users, which were mainly identified based on the analysis of existing prototypes of tangible maps and diagrams, and which include the design of tangible objects (which should allow for the representation to be relatively stable, complex and expressive), and the design of suitable interaction techniques and feedback (which should allow users to perform various tasks such as reconstructing or editing a map or a diagram).

From a theoretical perspective, the contributions of this chapter are twofold: we proposed a new classification and systematic analysis of existing prototypes of interactive maps and diagrams, and we provided a detailed analysis of existing prototypes of tangible maps and diagrams for visually impaired users. In the following chapters, we described how we addressed several design challenges by developing three tabletop TUIs that can give visually impaired people access to physical and updatable maps and diagrams, and support different tasks: the Tangible Reels, the Tangible Box, and BotMap.

CHAPTER 3

TANGIBLE REELS: CONSTRUCTION AND EXPLORATION OF TANGIBLE MAPS AND DIAGRAMS

> *Je précise immédiatement par souci de clarté que je ne fais pas de digressions, alors que je m'étais rendu au* Ramsès *pour consulter l'abbé Joseph, mais que je suis, dans ce présent traité, le démarche naturelle des pythons […]. Cette démarche ne s'effectue pas en ligne droite mais par contorsions, sinuosités, spirales, enroulements et déroulements successifs, formant parfois des anneaux et de véritables nœuds et qu'il est important donc de procéder ici de la même façon, avec sympathie et compréhension.*
>
> Romain Gary (Emile Ajar). Gros-Câlin.

Chapter structure

Related publications

J. Ducasse, M. Macé, M. Serrano, C. Jouffrais. *Tangible Reels: construction and exploration of tangible maps by visually impaired users.* CHI'16, 2186–2197. Regular paper.

J. Ducasse, M. Macé, M. Serrano, C. Jouffrais. *Tangible maps for visually impaired users: shape-changing perspectives.* CHI'16. Workshop paper.

1 INTRODUCTION

1.1 MOTIVATIONS

In Chapter 2, Part B, we described various techniques that are used to make visual representations accessible to visually impaired users. Unlike tactile maps and small-scale models, magnetic boards and corkboards allow the production of graphics that can be quickly updated by adding, removing or displacing objects (whether magnets or pins). These prototypes are non-permanent (and therefore easy to store), low-cost and easy to make. However, they generally require the presence of a sighted person to help the users place the objects in their right place. Besides, no legend can be provided because unlike the representation itself, the legend cannot be dynamically edited. Their lack of interactivity also limits the type of activities that these constructed graphics can be used for. Finally, maps and diagrams that are reconstructed with magnets or pins are very simple: for example, magnetic maps often consist of a sequence of very few rectangular magnets representing route segments (as in [272]). Despite these limitations, these graphics with movable parts are a good example of how physical and updatable representations can be useful for making visual representations accessible to visually impaired people.

The first project of this thesis was inspired by these two techniques. Our motivation was to design a system that would enable visually impaired users to construct their own physical and interactive maps (that is to say tangible maps), without the help of a sighted user. We wanted these tangible maps to present the same benefits as the ones made with magnets (low-cost, easy to make and to manipulate) while overcoming their limitations (lack of interactivity and the presence of a sighted user required). To do so, we designed a tabletop TUI as well as an innovative type of tangible objects, called Tangible Reels, that are used to make digital points and lines tangible. The user is progressively guided by audio instructions to place these objects in their right place, until the whole map is reconstructed. The user can thereafter interact with the map to retrieve the names of the points and lines.

1.2 SCENARIOS

This project was mainly driven by two scenarios. Even if these scenarios do not encompass all the possibilities for our interface, they illustrate its potential applications and uses.

The first scenario is closely related to the increasing availability of open data, and particularly of georeferenced data, which opens new perspectives for the automatic adaptation of visual maps into maps accessible without vision (see Chapter 2, Part B, 4.1). Such perspectives make it necessary to design and develop prototypes that could be used by visually impaired users to instantly and independently access maps, as sighted users do when exploring online maps. We envisioned that our interface could act as a “refreshable” device to display physical maps. In this scenario, our tangible tabletop interface is available in a public place. Visually impaired users can choose any country, city or region they wish to explore and select which information they would like to access. They would then reconstruct the map and explore it. For example, a newcomer to a city could display and explore the main points of interest of the city in order to understand their relative location, as well as the main avenues and streets, and, optionally, subway or bus lines. In addition, the active role played by the users could facilitate learning.

In the second scenario, our tangible interface is a pedagogical tool, very similar to the magnetic board, which can be used by visually impaired pupils to independently study a map as part of their curriculum for geography and Orientation & Mobility or a diagram as part of their curriculum for geometry. The process of physically reconstructing the map or diagram helps them to remember and understand it while making learning more playful. Because the presence of the teacher is not required, the pupils can access the graphic between two sessions, which enable them to consolidate their knowledge.

1.3 RESEARCH QUESTIONS

Throughout this project, we aimed at answering the following research questions:

- **How to design tangible objects that can be easily manipulated by visually impaired users?** Previous research studies suggest that the design of tangible objects for visually impaired users can be particularly difficult (see Chapter 2, Part E, 4.3). We aimed at designing objects that would take into account existing design considerations (e.g. stability) while fulfilling additional requirements specific to our interface (e.g. lines of varying lengths).
- **How to design interaction techniques for the construction and exploration of maps[39]? Are these interaction techniques usable?** In Chapter 2, Part E, 3, we described several projects aimed at the construction and exploration of tangible graphics. However, none of them clearly indicated how the user was guided to place an object in its right place. We aimed at filling this gap by designing and evaluating interaction techniques for the reconstruction and exploration of tangible maps.
- **What type of maps can be reconstructed and explored with a tangible tabletop interface?** We previously discussed limitations that are inherent to tangible interfaces (Chapter 2, Part D, 2.5): limited numbers of tangible objects (i.e. limited resolution), expressiveness, etc. We wanted to investigate whether these limitations could be overcome, and if so, to what extent.
- **Are the tangible maps built with our interface understandable? Does reconstructing a tangible map help a visually impaired user learning it?** The purpose of evaluating our interface was to ensure that users could understand tangible maps built with the Tangible Reels. In addition, we wanted to start investigating to what extent the active reconstruction of maps and diagrams could be beneficial in terms of understanding and/or learning.

1.4 CHAPTER STRUCTURE

In section 2 we first describe how the Tangible Reels were designed, from requirements analysis to the prototypes used in the experiments. In section 3 we report on a preliminary study that we conducted with four visually impaired users to evaluate the usability of the Tangible Reels. We then describe the design of the interaction techniques for the construction and exploration of the tangible maps (section 4) as well as the implementation of the interface (section 5). In section 6 we present the evaluation of the system that we conducted with eight visually impaired users and

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[39] For this project, we initially focused on maps. However, in section 8.3 we discuss how the Tangible Reels could be easily adapted to different types of diagrams.

report and discuss the results of this evaluation. In section 7, we briefly report on a pedagogical workshop that we organized in collaboration with a teacher from the IJA and during which three pupils used the interface. Finally, in section 8, we discuss the advantages and limitations of the prototype and suggest various perspectives.

2 DESIGN OF THE TANGIBLE REELS

2.1 REQUIREMENTS

As we said earlier (Chapter 2, Part A, 2), the graphical primitives of a map are points, lines, and areas. For a map to be fully tangible, all of these primitives should be transcribed into physical and interactive forms. Although it is possible to make digital points and lines physical, making digital areas physical is much more challenging, due to the unlimited variety of shapes that exist. In this project we therefore focused on maps that are only composed of points and lines. In section 8.2 and Chapter 6, 4.1.3 we discuss how areas could be made accessible through gestural interaction and audio feedback.

We identified six main requirements: 1) the tangible objects must be designed so as to physically render digital points and lines of different lengths; 2) the tangible objects must be tracked so that the system can provide feedback according to their position; 3) each tangible object has to be uniquely identified because it is associated with a particular piece of information; 4) the tangible objects must be stable during the exploration [196] and easy to move during the construction; 5) whatever the technology used to identify and track the objects and the techniques used to make digital lines tangible, the tangible objects have to be as small as possible in order to maximize the number of objects that can be placed onto the tabletop: in this way the interface could be used to construct maps of varying complexities.

To fulfill these requirements a number of prototypes were designed and tested by our colleagues, one of whom being visually impaired and another blind. In the following sections, we detail how we took into account each of the mentioned requirement.

2.2 DESIGN RATIONALE

2.2.1 IDENTIFYING AND TRACKING SMALL OBJECTS

In Chapter 2, Part D, 3.1, we described and summarized various technologies that can be used to track objects when designing a tabletop TUI. Because the objects would often be manipulated by the user, we wanted to avoid any occlusion that may happen when the objects are tracked by a camera mounted above the table and therefore excluded this possibility. We also excluded technologies based on a matrix of RFID tag readers as they are expensive and not commonplace. As for technologies that use a camera placed below the tabletop, we indicated that their main limitation is the size of the objects. Indeed, because a translucent surface is used to project an image onto the table, the tag fixed under the objects is perceived as blurred by the camera. The same limitation applies to interactive tables. Consequently, we decided not to project any image, so that we could simply use a transparent glass surface. A camera is placed under the glass surface and the tags size can be reduced.

Two computer vision libraries that support the detection of small tags were compared: ARToolKit [134] and TopCodes [103]. TopCodes markers are circular and ARToolKit markers are square. For similar markers' widths, we achieved better tracking with the TopCodes library and therefore chose it.

2.2.2 MAKING DIGITAL LINES TANGIBLE

Using several objects of various lengths can be cumbersome (see Chapter 2, Part E, 4 for examples). To tackle this issue, we wanted to provide users with a single object that could be used to represent lines of various lengths. A number of solutions were investigated, including the use of elastics. However, we did not find elastic bands that could be sufficiently extended to various lengths without exerting too much force. Retractable reels appeared to be an appropriate tool, as their string can be easily extended to various lengths. They are small objects composed of a string and a small spring that makes the string retract. They are often used on badges, retractable meters or USB cables (see Figure 3.1). Retractable badge reels can be of various sizes and materials, and can be easily found online at a very low cost (around 2€). One downside of traditional retractable reels is that the string can retract suddenly. We therefore use retractable reels with a lock/unlock button: the string only retracts when the button is pressed.

Figure 3.1. To make digital lines tangible, retractable badge reels were used. The string can be pulled out at different lengths.

2.2.3 DESIGNING STABLE AND EASY-TO-MOVE OBJECTS

According to McGookin et al. [196] tangible objects must be stable in order to stay in position during exploration. Designing stable objects was even more important in our case as tension was applied to the objects by the strings of the retractable reels. However, the stability of the objects should not prevent the user from easily moving them when reconstructing the map. We particularly wanted the user to be able to lift them up to quickly reach any part of the table.

EXISTING SOLUTIONS

In Chapter 2, Part E, 3, we described existing tabletop TUIs for visually impaired users. Among them, only [196] and [272] took into consideration the stability of the objects. McGookin et al. [196] used a tangible grid made out of straws combined with weighted objects. However, the authors report that several objects were knocked over by the users during the evaluation. Besides, the usage of a grid limits where the objects can be positioned on the table. In [272] the objects were linked to each other using magnets, but the authors did not indicate how the whole structure was held in place.

As for tangible interfaces for sighted users, to our knowledge, the stability of the objects has only been considered for non-horizontal surfaces. Hennecke et al. [99] compared a number of adhesion technologies using several criteria: sensing (optical, resistive, capacitive or inductive), output (front-projection, rear-projection or LCD), and TUI characteristics (transparency, passivity, movability and reusability). These technologies include magnets, glue and electro-adhesion, as well as vacuum-based adhesion. The downside of magnets is that they cannot be used with rear-projection, unless each object is composed of two magnets placed on either side of the surface (see Chapter 3). However, in that case, the objects cannot be lifted up. Glue loses adherence over time and is therefore not re-usable. Electro-adhesive pads are compatible with rear-projection, are movable and reusable but are based on continuous power consumption, which necessitates additional and expensive hardware. As for vacuum-based adhesion, it consists in using "an adhesive film with artificially created microscopic suction cups". A well-known example is the adhesive pads that can be stuck on a car's dashboard to hold keys, smartphones, etc[40]. Hennecke et al.'s tangible objects, called Vertibles, are based on such an adhesive film. A preliminary study showed that the objects did not fall down during the time of the observation. However, the authors also indicate that these objects were not easily movable as the users needed to detach and replace them instead of sliding them.

PROPOSED SOLUTIONS

Similarly to Hennecke et al. [99], we tried a number of adhesive materials such as Blu-Tack[41], glue dots[42], adhesive tape, Wikki Sticks[43], anti-slip gel pads or electrostatic screen protectors but none of them fulfilled the two above mentioned requirements: being stable during exploration and easy to move. Finally we ended up with two types of objects: plastic cylinders filled with lead called Weights (see Figure 3.2, left), and flat Sucker pads (see Figure 3.2, middle).

Weights were inspired by the authors of the Tangible Graph Builder [196], who suggested varying the weight of the tangible objects to ensure stability. After several tests with a visually impaired user, we found that filling a 6 cm high and 4 cm wide cylinder with 180 g of lead was adequate. To further improve adherence of the Weights, a silicone O-ring was added under the base. The tag used to track the objects was placed inside this ring (see Figure 3.2, right). The base and the top of the cylinder were made out of a thick cardboard strongly glued to the cylinder. The reel was then glued to the top of the cylinder, and its string was passed through a hook fixed at the bottom of the cylinder (1 cm high) to keep it close to the tabletop.

Concerning sucker pads, they can easily slide along a smooth surface such as the tabletop screen, and strongly stick to the screen when pressed. We tried and compared a number of sucker pads. Those with a lever hook were very stable but it was difficult to attach the reel to the top of them. Using several mini sucker pads for one object was not sufficient enough, as they detached very easily. We finally opted for professional flat sucker pads (4 cm wide and 2 cm high once compressed) that present a large surface under which a tag can be attached (Figure 3.2, right). Besides, as sucker pads can be hard to remove once pressed, we chose sucker pads with a small strip that extends from its base to easily remove it. The reel was glued on top of the sucker pad.

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[40] See http://www.nano-pad.com/en/index.html for example

[41] https://en.wikipedia.org/wiki/Blu-Tack

[42] See http://www.gluedots.com/index.html for example

[43] https://www.wikkistix.com/

Figure 3.2. Final design of the two types of Tangible Reels. A Tangible Reel is composed of a retractable reel, a metallic bracelet and magnet. Left: Weights are composed of a plastic cylinder filled with lead; they are 6 cm high and 4 cm wide. Middle: Sucker pads are 2 cm high and 4 cm wide. Right: bottom view of the Tangible Reels with the TopCode tag visible.

2.3 FINAL DESIGN

To make it possible to link two objects together we fixed a strong neodymium magnet at the extremity of the reels' strings and added a metallic bracelet to the objects. In this way one can easily attach the extremity of a string to any part of the second object without having to locate a hook (Figure 3.3). The bracelet was wrapped around the bottom part of the cylinder for the Weights and around the reels for the Sucker pads.

Figure 3.3. By attaching one Tangible Reel's retractable string to a Tangible Reel's metallic bracelet, a physical line can be built between two Tangible Reels. A strong neodymium magnet is attached at the end of each string.

3 PRE-STUDY: USABILITY OF THE TANGIBLE REELS

The aim of this study was to investigate whether the two types of Tangible Reels were stable and easy to manipulate, but also to verify that tangible maps built with them were understandable by visually impaired users.

3.1 STUDY DESIGN RATIONALE

3.1.1 TASK CHOICE

Since our interface enables visually impaired users to construct and explore tangible maps, we designed two tasks: one exploration task during which the user had to explore a map with their hands before drawing it; one construction task during which the user had to manipulate the objects (i.e. placing them, eventually moving them, and attaching several objects together) to reproduce a model map as accurately as possible.

3.1.2 QUESTIONNAIRE

To evaluate users' satisfaction, we used a questionnaire and asked the participants to rank the objects according to their preference. Because this study focused on the usability of objects, standard usability questionnaires such as the SUS [25] were not appropriate, as they are rather meant to evaluate the usability of interactive and standalone systems. We therefore designed our own questionnaire, inspired by the one used by Kane et al. [133]. The questionnaire is further described in section 3.2.2.

3.1.3 ASSESSING MENTAL REPRESENTATIONS

We assessed the quality of the participants' spatial representations constructed during the exploration task. In section Chapter 2, Part A, 3.3.1, we described various methods that can be used to assess spatial representations of visually impaired users. Methods based on questions could not be used for this study because the points and lines were not labelled (and they were not interactive). Users were therefore asked to sketch the map on German paper[44]. As drawing can be difficult in the absence of vision, participants also had the possibility to sketch the map using a set of magnets and a magnetic board.

The degree of resemblance between a sketched map and a model map can be obtained by a bidimensional regression analysis or by asking external judges to mark the sketches. Whereas the first method is certainly more objective, it is based on the coordinates of points only. In the absence of labels, and particularly when the maps are incomplete, identifying these points can be difficult. We therefore asked external judges to mark the sketched maps by following a set of precise instructions, as in [38,320].

3.1.4 MAPS

The complexity of the map that can be built with our interface is limited by the size of the objects. However, it is possible to construct relatively complex configurations, even with a limited number of objects. We hypothesized that the complexity of the map displayed could impact the usability of the Tangible Reels as well as the quality of the participants' spatial representations, especially when several lines are crossing each other. We therefore decided to use maps of various complexities and as realistic as possible.

To do so we used two types of maps: Metro maps and Overview maps. For Metro maps, points represent Metro stations while lines represent connections between stations. Concerning the second type of maps, the Braille Authority of North Canada [299] defined Overview maps as maps that "may not have specific detail that would allow some readers to plan a walking route, but instead are designed to familiarize and orient the reader with the area encompassed". The Overview maps that we designed were inspired by a map used by an Orientation & Mobility teacher working at the IJA, presented in Figure 3.4, left.

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[44] See Chapter 2, Part B, 2 for an illustration of a sheet of German paper.

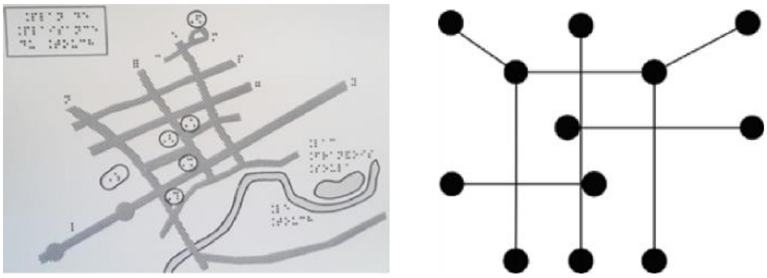


Figure 3.4. Left: Example of an Overview map used at the IJA. Right: an Overview map for the pre-study.

3.2 MATERIAL AND METHODS

3.2.1 PARTICIPANTS

We recruited four legally blind persons (two female, two male) aged between 31 and 65 years (*M* = 48.2, *SD* = 14.9). Table 3.1 gives the participants' characteristics.

Table 3.1. Participants' main characteristics: age, gender, degree of visual impairment and age at onset of blindness.

Participant	Age	Gender	Residual perception	Age at onset of blindness
P1	42	Male	Bright stimulus	1
P2	65	Male	No	5
P3	55	Female	No	6
P4	31	Female	No	12

3.2.2 MATERIAL

MAPS

Two Metro maps and two Overview maps were designed for each of the tasks (Figure 3.5 and Figure 3.6). Each Metro map was composed of 9 Tangible Reels and 8 lines. Each Overview map was composed of 12 Tangible Reels and 8 lines.

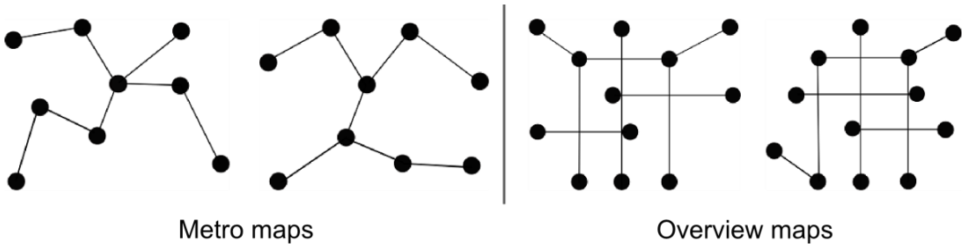


Figure 3.5. Maps used for the exploration task.

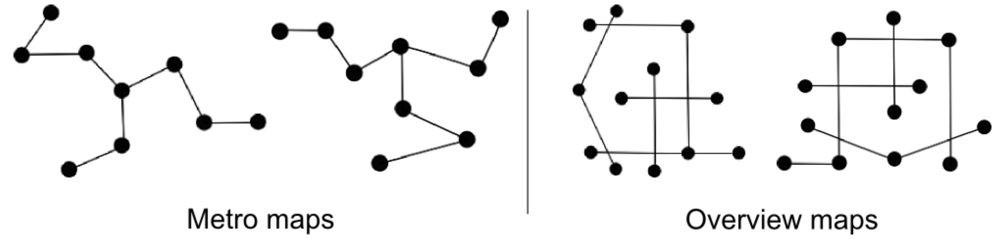


Figure 3.6. Maps used for the construction task.

QUESTIONNAIRE

The participants specified on a 7-point Likert scale their level of agreement with a series of statements (1 = strongly disagree and 7 = strongly agree) for each task and each object design. The first five items were:

- Building/exploring a map with these objects is pleasant.
- Building/exploring a map with these objects is difficult.
- Building/exploring a map with these objects is fast.
- Building/exploring a map with these objects is frustrating.
- It is easy to unintentionally move or knock over the objects.

In order to get a subjective rating of the readability of the maps by the participants, a sixth item was added for the exploration task only: "The objects allowed me to understand the map".

3.2.3 TASKS

The exploration task consisted in exploring one Metro map and one Overview map that had been previously constructed by the evaluator. Participants had respectively three and four minutes to explore those maps, and immediately after the exploration had to draw the map. They were asked to do it as accurately as possible, focusing on the topology rather than the distances. To draw the maps, three subjects used a sheet of German paper and one subject, who was not familiar with German paper, used magnets on a board. This participant was provided with several magnets of various lengths. Other participants were provided with a rule (without tactile cues). The time to draw the map was not limited.

The construction task consisted in reconstructing as accurately as possible two maps with the Tangible Reels. Participants were shown a raised-line map and had to memorize it before reconstruction. No time limit was imposed for the memorization or the construction. Once they started constructing the tangible map, they could not explore the raised-line map again.

3.2.4 EXPERIMENTAL DESIGN

For both tasks, we used a within-subjects design with two independent variables:

- **Object design**. We evaluated the two object designs described below: the Sucker pads and the Weights.
- **Map**. Two types of maps were used: Metro maps (9 Tangible Reels) and Overview maps (12 Tangible Reels).

The order of the blocks was counterbalanced among the users. We also counterbalanced the two sets of maps, each containing one Metro map and one Overview map for the exploration, as well as one Metro map and one Overview map for the construction.

3.2.5 MEASURES

The stability of the Tangible Reels was measured during the exploration task. The position of the objects before and after the exploration was recorded using a Java application. We then computed the distance between the position of each object before and after the exploration. We also counted the number of times a Sucker Pad was detached or moved as well as the number of times a Weight was knocked over.

In order to assess participants' spatial knowledge, we presented the sketched maps to four independent judges who were not involved in the project, alongside pictures of the maps that had been explored. The maps that were made with magnets (Participant 4) were accurately reproduced on German paper. We asked the judges to evaluate the correctness of the drawn maps compared to the model: 0/10 means that the two maps were not similar at all; 10/10 means that the two maps were highly similar. We asked the judges to focus on the topology of the map rather than on distances. Before marking the maps, judges were shown three examples of drawings that should receive 0, 5 and 10.

3.2.6 PROCEDURE

Participants were welcomed and were explained the purpose of the tangible interface and the Tangible Reels, as well as the experiment. The study was made up of two blocks corresponding to the two designs (Weights and Sucker pads). One block consisted in training followed by the exploration task and finally the construction task. During the training phase, participants were told how to construct a line by attaching two objects together. They could practice until they felt comfortable. For both the exploration and construction tasks, a Metro map was presented and then an Overview map. After performing the exploration task and the construction task, participants answered the questionnaire. The procedure for one block is summarized in Figure 3.7. At the end of the session, participants ranked the object designs according to their preference and were invited to comment on the Tangible Reels.

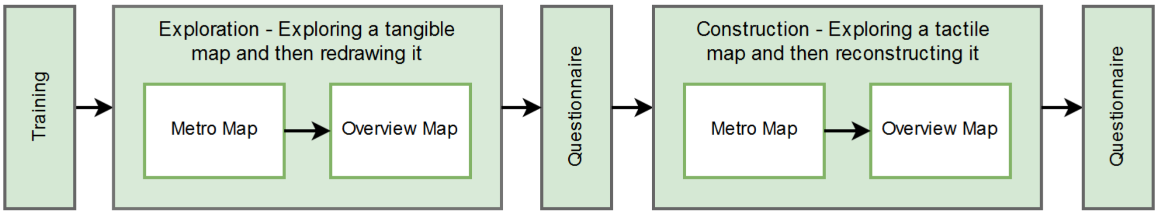


Figure 3.7. Summary of the procedure for one Tangible Reel design. The procedure was repeated for the Sucker Pads and the Weights.

3.3 RESULTS

3.3.1 TANGIBLE REELS USABILITY

EXPLORATION AND CONSTRUCTION

The average distance in centimeters between the positions of the objects before and after the exploration of the maps was 0.28 cm (*SD* = 0.03) for the Weights and 0.08 cm (*SD* = 0.01) for the Sucker pads (see Figure 3.8 for a photography of one participant exploring the map). During all the explorations, one Sucker pad got detached; none were moved. P1 almost knocked over three Weights, and P3 knocked over two Weights. It should be noted that one Metro map and three Overview maps constructed by the participants were not similar to the model. The subjects indicated that they could not remember the whole raised-line map.

Figure 3.8. Exploration of a map built with Tangible Reel by a visually impaired participant.

QUESTIONNAIRE

Table 3.2 shows the percentage of agreement for each statement.

Table 3.2. Percentage of subjects who answered a 5, 6 or 7 for each item and Object Design after the exploration and the construction tasks. The darker the cell, the higher the value.

Task	Design	Pleasant	Difficult	Fast	Frustrating	Easy to knock over	Helpful
Explo.	Weights	25%	25%	50%	25%	50%	75%
	Sucker Pads	100%	0%	50%	0%	0%	100%
Constr.	Weights	75%	0%	100%	25%	50%	-
	Sucker Pads	100%	0%	75%	0%	0%	-

RANKING

All the participants preferred the Sucker pads for the exploration task but results were mixed for the construction task: two preferred the Sucker pads and the other two the Weights. Overall, three participants preferred the Sucker pads as a global best choice.

QUALITATIVE FEEDBACK

Concerning the Weights, two participants stated that when they had to replace several objects it was easier to do so with the Weights rather than with the Sucker pads (P2, P4). P3 stated that as they could be easily moved, it was easy to adjust their position when constructing the map. Participants reported concerns when exploring the map with the Weights: P2 declared that he “missed one object because [he] was paying attention to not knock them over”. The same issue was reported by P1 who said that he was “afraid of knocking them over” and that they hindered the exploration. Two participants also reported that the height of the Weights was an issue, rather than their diameter (P1, P3).

As for the Sucker pads, three participants said that their reduced height allowed them to better explore the map (P1, P3, P4), and two stated that there were fewer risks in moving them during the exploration (P1, P4). P4 also declared that “the advantage is that they do not take up a lot of place” while P3 described the sucker pads as “cool”, “light” and “fun”. P4 said that “attaching and detaching the Sucker pads is a little bit annoying”.

3.3.2 MAP DRAWINGS

Figure 3.9 and Figure 3.10 show examples respectively of Metro map and Overview map drawings (all drawings are presented in Appendix A). The average marks given were 8.1 (*SD* = 1.3) for the Metro maps and 5.7 (*SD* = 2.7) for the Overview maps. P4 obtained the lowest marks for the Overview maps (1.5 and 2.5). If we exclude her marks, the average mark for the Overview maps was 7.0 (*SD* = 1.4).

Metro Map Model

Mark: 5,25

Mark: 8,5

Mark: 8,6

Mark: 9,63

Figure 3.9. Examples of Metro maps drawings made by the participants, alongside their average mark.

Overview Map Model

Mark: 2,25

Mark: 6,00

Mark: 7,25

Mark: 8,44

Figure 3.10. Examples of Overview maps drawings made by the participants, alongside their average mark.

3.4 DISCUSSION

Both types of Tangible Reels proved to be easy to manipulate by a visually impaired user. Over the four Object Design * Tasks conditions, only one participant considered that building a map with the Tangible Reels was difficult while the majority found it pleasant. The Sucker pads appeared to be more stable than the Weights. This is coherent with the fact that two participants found that the Weights were easy to unintentionally knock over. One drawback of the Sucker pads is that they cannot be removed as easily as the Weights. However, it should be noted that participants had to remove the Sucker pads several times during the construction task in this pre-study. This is unlikely to happen in a real scenario because the users would be guided by audio feedback. Several participants also reported that the height of the Weights hindered the exploration, and two participants knocked some Weights over. To sum up, it appeared that Sucker pads better meet the stability requirement, and that they were globally preferred by three participants. According to these observations, and even though we do not consider that Weights were unusable, we chose the Sucker pads for the following experiment.

The marks attributed to drawings show that maps constructed with Tangible Reels can be explored and memorized by visually impaired users. Three out of four participants found that the Tangible Reels allowed them to understand the map. However, the existence of incorrect drawings showed that some participants experienced difficulties, especially with Overview maps that were more complex. Indeed, three participants said that they were quite difficult to understand and memorize. This observation suggests that the maps built with Tangible Reels should not be too complex. In the follow-up study, we specifically investigated the effect of map complexity on the usability of Tangible Reels.

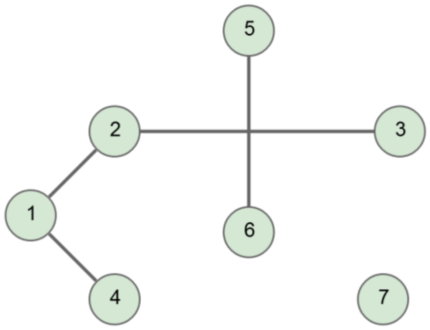
4 INTERACTION TECHNIQUES AND FEEDBACK

At the beginning of the construction Tangible Reels are placed next to the user, on the bottom side of the table. Audio instructions and feedback are provided so that the user can gradually construct a simple physical representation of the map by placing the Tangible Reels. During exploration, the user can retrieve the name of the points and lines by pointing the points and lines of the map with a finger. All the values mentioned afterward (distances and timers) were based on observations made during preliminary tests.

4.1 RECONSTRUCTION

4.1.1 ORDER OF RECONSTRUCTION

Each map is defined by a set of points and a set of lines, each line being itself defined by one starting point and one end point. Points are represented by Tangible Reels; lines are represented by two Tangible Reels connected to each other with a retractable string.



```
lines.add(new Line(1,2));
lines.add(new Line(2,3));
lines.add(new Line(1,4));
lines.add(new Line(5,6));

points.add(7);
```

Figure 3.11. Example of a map and its corresponding description file (simplified version). Numbers indicate the order of reconstruction.

Users construct the lines in the order they appear in the file containing the map description. Points are reconstructed after the lines in order to facilitate the construction of lines. We tried as much as possible to describe the map from top to bottom and from left to right, so that the reconstruction will follow the same order. In this way we wanted to follow the reading direction. In addition, when exploring a tactile map, visually impaired people are taught to first scan the map using both hands, from top to bottom and from left to right. Figure 3.11 presents a map and a simplified version of its description.

4.1.2 PROCEDURE FOR CONNECTING TWO TANGIBLE REELS

To connect two objects together, two procedures were investigated. The first one is to guide the user to place the two objects separately, and then to ask the user to pull out the string of one object and attach it to the correct object (which is not necessarily the last one placed). This is similar to TIMMs [182], where the authors suggest that once the objects are placed, a tactile line can be added. However, by doing so, the number of steps required is high: placing the first object, placing the second object, relocating the first object while holding the string of the second object, attaching the string to the first object. Besides, with this approach, the system cannot detect when two Tangible Reels are connected, unless the user performs another action such as double-tapping on the two Tangible Reels or following the line with a finger.

Another solution consists in placing the first Tangible Reel and then connecting the second one, before following guidance instructions. By doing so, the string is being pulled out as the user moves the second Tangible Reel. Therefore the user does not need to relocate the first Tangible Reel. The system is also able to detect that the two objects are connected whenever they are close enough to each other, thus sparing the user another action. We opted for this solution, illustrated in Figure 3.12.

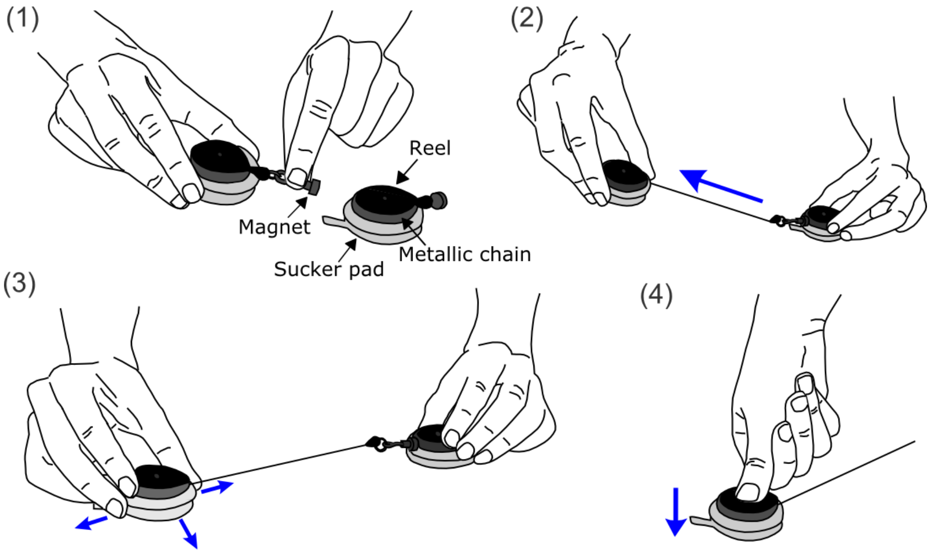


Figure 3.12. Procedure for connecting two Tangible Reels in order to build a line. First, the user must attach a Tangible Reel to another one (1). Then, the user follows guidance instructions (2 et 3) before firmly pressing the sucker pad (4).

4.1.3 INSTRUCTIONS

RECONSTRUCTION

When reconstructing the map, the user either has to place a new object (to start constructing a line or to place a point, see Points 1, 5 and 7 in Figure 3.11) or to connect an object to an object already placed (to finish constructing a segment, see Points 2, 3, 4 and 6 in Figure 3.11). In that case, the object already placed can be the last object that the user has placed, or another one. We therefore defined three instructions that indicate to the user the next action to be performed:

- *"**New object**"*. At the very beginning of the construction and each time a new line has to be built, the user has to place a Tangible Reel on the table (i.e. without attaching it to a previous one). As soon as the Tangible Reel is detected, guidance instructions are provided.
- *"**Attach an object to the right/to the left/below/above**[45]"*. To construct a line the user has to pull out the string of a new Tangible Reel and attach it to the metallic bracelet of the previous one placed. As soon as the system detects that the two objects are connected (i.e. when they are close enough to each other), guidance instructions are provided.
- *"**Attach an object to <name of the object>, to the right/to the left/below/above**"*. The starting point of the line to be built is not always the last Tangible Reel that the user has placed. In this case the system gives the name of the object to which the new Tangible Reel must be attached, so that the user can relocate it. As soon as the system detects that the two objects are connected, guidance instructions are provided.

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[45] During informal tests we observed that giving the direction to which the user must attach the Tangible Reel was beneficial to avoid the user detaching/reattaching the magnet depending on the following guidance instructions. Also, if the string is not attached in the right direction, it does not form a straight line between the two objects, which creates a mismatch between the physical and the digital lines.

GUIDANCE

Guidance instructions are provided to the users to allow them to place the Tangible Reels in their right place. A number of studies have investigated how to help users (re)locate points of interest on a virtual map or environment, in the absence of vision. We briefly describe some of them before introducing an innovative two-step guidance technique.

Existing solutions

In Access Overlays [133] visually impaired users are provided with spoken directions to help them relocate points of interest on a large interactive table. Depending on the distance and direction of the target, users first move their finger horizontally (resp. vertically) and then vertically (resp. horizontally). For each movement users are first told the distance and direction of the next intersection and are provided with spoken directions ("down", "up", "left", "right") until they reach it. The direction and distance of the next point is then given and the procedure repeated. This technique was later used by Simonnet et al. [284].

Camors and al. [4] proposed a guidance technique to help visually impaired people locate a point of interest in a virtual environment. Participants were equipped with a bracelet composed of several vibrating motors. Vibrations indicated the coordinates of the target on a Cartesian plan. Results showed that participants were able to interpret these vibrations to quickly find the target. These techniques can be qualified as semi-ballistic because they enable the users to quickly approach the target, but the movement must be performed in two steps (e.g. horizontally, then vertically).

It is also possible to provide the users with the effective direction of the target, enabling them to directly move towards it. For example, Bardot et al. [5] proposed a technique that enables visually impaired users equipped with a smartwatch to find an on-screen target: users first draw a circle clockwise with their finger on the screen; as soon as their finger indicates the right direction, the smartwatch vibrates and users can follow the specified direction[46].

Besides vibrations and traditional spoken directions (up, left, right and down), it is also possible to describe directions using the clock face, where "noon" means up, 3 o'clock mean right, 8 o'clock means down and left, etc. A technique based on this metaphor was successfully implemented and evaluated with blindfolded participants as part of my master thesis [49]. It was inspired by the fact that some blind people use clock face directions during Orientation & Mobility lessons.

Proposed solution

Our solution combines the idea of ballistic guidance with the idea of providing precise directions using the analogy of a 12-hour clock. Depending on the distance between the Tangible Reel that the user is currently moving and the position of the target, two types of guidance instructions are provided: rough guidance instructions (every 3500 ms) and fine guidance instructions (every 1500 ms):

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[46] It should be noted that in that case users were already close to the target thanks to another technique that allowed them to retrieve the names of the targets displayed within a cell of a virtual grid overlaid on the map.

- **Rough guidance instructions** (Figure 3.12, b). When distance is superior to 15 cm, the system indicates the direction of the target (up, up and right, right, down and right, etc.) as well as the distance in centimeters. This enables the user to either quickly slide or lift the object towards the target.
- **Fine guidance instructions** (Figure 3.12, c). When the distance to the target is inferior to 15 cm, the system provides more frequent feedback to indicate the direction to follow (up, right, down, left). As long as the target has not been reached, the system repeats the procedure.

There may be a delay between the time when the system detects that the Tangible Reel is correctly placed and the time when the "found" feedback is played. Therefore, users may sometimes keep moving the Tangible Reels before the feedback "found" is played. In that case, guidance instructions are given again. A Tangible Reel is considered as correctly placed when it is less than 2 cm away from its correct position for at least 1.5 seconds. The state-machine used to handle the guidance process is provided in Appendix A.

4.1.4 FEEDBACK

Besides the above-mentioned instructions, different vocal feedbacks are given:

- **"*Attached*":** This instruction is played when the system detects that the new Tangible Reel is close enough to the one that it must be attached to, and is immediately followed by guidance instructions.
- ***"<Name of the point> found"*.** The system informs the user when the Tangible Reel is at the right location by giving the name of the point represented by the Tangible Reel. If the Tangible Reel is the end point of a line, the instruction *"<name of the line> built"* is played next.
- ***"Over"*:** this instruction is played when the last point has been placed, i.e. when the reconstruction is over.
- ***"Object lost"*:** The user is informed if the Tangible Reel that is being moved has not been detected by the system for more than 2500 ms.

The last instruction is repeated every 7000 ms until the appropriate action is done by the user. When the *"attach an object"* instruction is repeated, the name of the object to which the user must attach a new Tangible Reel is also given. The state-machine used to handle the reconstruction process is provided in Appendix A.

4.2 EXPLORATION

We considered tangible and gestural interaction techniques to enable the users to interact with the Sucker Pads. However, the use of a tangible tool can be problematic because it requires the users to keep track of the tool, which might slow down and disrupt the exploration process. For these reasons we did not choose tangible interaction techniques.

As for gestural interactions, we considered three technologies: using a camera placed above the tabletop to track a user's finger to which a marker would be attached; using a multitouch foil; using an infrared multitouch frame. The technical aspects of these last two solutions have been thoroughly described in Chapter 2, Part D, 3.2. Using two cameras would have increased the cost of the system. Also, from a technical point of view, managing two different video inputs can be challenging. Both a multitouch foil and an infrared multitouch frame provide the application with finger touches positions, but some touches can be omitted by the multitouch frame if the rays that are used to detect the finger inputs are obstructed. The advantage of multitouch frames relies in their low price and relatively good resolution, as compared to multitouch foils. In order to overcome the limitation associated with the obstruction of finger touches by objects, we placed the infrared frame on a two centimeters high wooden frame (see Figure 3.13, left). Thus only the fingers are detected by the frame and not the objects, making it a suitable and low-cost solution to detect users' gestures on top of the Tangible Reels and their strings.

A specific gesture had to be found to avoid unintentional selections. The disadvantage of multitouch gestures is that they can be easily performed unintentionally [24]. We found that constraining the users to use one finger only to select an object or a line limited the number of unintentional selections. We eventually chose a "tap and hold" gesture to make the gesture more easily identifiable (Figure 3.13, right). Feedback is provided when the object has been "tapped and held" for more than 700 ms. Besides, it is possible to select the objects and the line only once the map is reconstructed. When a new Tangible Reel needs to be attached to another one, only the objects can be selected. As soon as the Tangible Reels are attached, the exploration mode is inactivated.

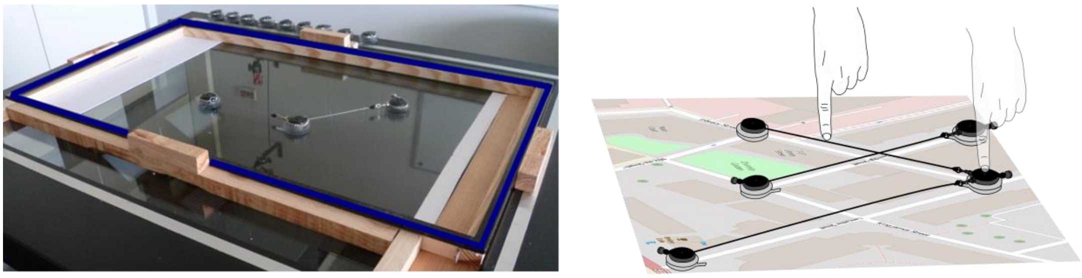

Figure 3.13. The system is composed of a transparent tabletop upon which an infrared frame (highlighted in blue, left) is placed to detect whenever the user performs a "tap and hold" gesture (right).

5 IMPLEMENTATION

5.1 HARDWARE

Our tabletop is a 100 x 100 cm plate glass. The setup also includes a projector to illuminate the surface and a webcam to detect the objects. Both are placed beneath the plate glass. A multitouch infrared frame is placed two centimeters above the plate glass (Figure 3.13, left) to detect the fingers. To achieve a high quality of tag detection, we restricted the area of work to 80 x 57 cm. A wooden frame is placed upon the tabletop to delimitate the working area. The projector, webcam and infrared frame are connected to a laptop (Dell Latitude E6430s, Windows 7).

5.2 SOFTWARE

Objects are tracked using the TopCode library [103], a free and open source Java library developed at the Tufts University Human Computer Interaction Lab in Medford, Massachusetts.

The TopCode library can be used to recognize up to 99 codes as small as 25 x 25 pixels. The library provides the location, orientation and diameter of each tag that is detected.

Finger tracking is done with the infrared frame placed above the table. The infrared frame sends messages containing the finger input state (pressed, updated or ended) and position using the TUIO protocol [129]. The TUIO protocol "allows the transmission of an abstract description of interactive surfaces, including touch events and tangible object states. This protocol encodes control data from a tracker application (e.g. based on computer vision) and sends it to any client application that is capable of decoding the protocol".

Audio instructions are provided with a SAPI4 compliant Text-To-Speech engine distributed as part of the CloudGarden TalkingJava SDK 1.7.0.

To receive TUIO messages, we used the MultiTouch4Java library [156], a JAVA platform built upon TUIO input. One advantage of MT4J is that it supports the development of graphical user interfaces. Even though no images were projected on the table, we used visual feedback for debug and demo purposes. The MT4J application manages the input (from the TopCode library and from the infrared frame) as well as the audio feedback.

6 MAIN STUDY: USABILITY OF THE INTERACTION TECHNIQUES

6.1 AIM AND STUDY DESIGN RATIONALE

The complexity of the maps that can be built by the system is limited by the size of the objects and the size of the working area. However, constructing and exploring complex maps can also lead to usability issues or be perceived as too difficult. Therefore, the aim of this study was to evaluate the usability of the whole interactive device with Sucker pads, and to investigate whether increasing the levels of complexity of the maps led to usability issues.

6.1.1 TASK CHOICE

Two tasks were designed: constructing a map and exploring it in order to answer three questions. We designed four maps of various complexities. The number of maps to be constructed was chosen so that the experiment would not exceed two hours. For the exploration task, because we wanted the user to select objects and lines, we used the following type of questions: *what are the names of the two points at the extremities of <name of a line>?*

6.1.2 QUESTIONNAIRES

In addition to quantitative and objective measures of usability, we wanted to assess the perceived usability of the system as well as the cognitive load required to perform the tasks.

Different instruments can be used to assess the perceived usability of a system, such as the Unified Theory of Acceptance and Use of Technology instrument [319], which is composed of a set of items related to eight constructs: performance expectancy, effort expectancy, attitude towards using technology, social influence, facilitating conditions, self-efficacy, anxiety and behavioural intention to use the system. However, this questionnaire, as most other instruments to assess perceived usability, is relatively long (see [23] for a review). On the contrary, the System Usability Scale questionnaire (SUS, [25]), which is composed of ten items that users must rate from 1 to 5, is a standardized, short and reliable questionnaire that is also very frequently used. Based on these considerations, we decided to use this questionnaire.

To assess users' cognitive load, a number of questionnaires based on subjective measures also exist (see [77] for a review). Some consider only one dimension (e.g. Mental Effort Rating Scale [321]) while others consider several dimensions (e.g. the Subjective Workload Assessment Technique [250], composed of three dimensions: time load, mental effort load and psychological stress load). However, one of the most common questionnaires is the NASA-TLX [94], which is also composed of several dimensions: three are related to the user; three are related to the task. For each dimension, users must rate the said dimension (e.g. mental demand) from 0 to 100. Although the full questionnaire includes a phase where users must weight each dimension, this phase is not necessary [29]. In this study, we decided to use the short version of the questionnaire, referred to as the NASA-RTLX (NASA-Raw Task Load index).

It should be noted that the use of validated scales such as the SUS and NASA-TLX questionnaires is particularly recommended in accessibility research to reduce positive bias that may be due, for example, to the use of verbally-presented questions or to the recruitment of participants "with a 'can-do' attitude, or a desire to encourage and support young researchers" [303].

6.2 MATERIAL AND METHODS

6.2.1 PARTICIPANTS

We recruited 8 legally blind persons (2 female, 6 male) aged between 24 and 65 (*M* = 43.8, *SD* = 14.4). Three were born blind; one became blind before the age of 1; three between 4 and 6 years old and one at 16. Three had residual light perception but were unable to discern shapes; others could not perceive anything at all. The following table (Table 3.3) describes the main participants' characteristics.

Table 3.3. Participants' main characteristics: gender, age, degree of visual impairment and age at onset of visual impairment.

Participant	Gender	Age	Residual perception	Age at onset of blindness
P1	Male	42	Very bright stimuli	1
P2	Male	65	No	5
P3	Female	42	Very bright stimuli	0
P4	Male	24	Very bright stimuli	16
P5	Female	55	No	6
P6	Male	30	No	0
P7	Male	34	No	4
P8	Male	58	No	0

6.2.2 MAPS

We designed four maps of different complexities (Figure 3.14). To do so we gradually augmented the number of points (6, 8, 10, 12), lines (5, 6, 7, 8), oblique lines (1, 2, 3, 4), crossings between lines (0, 2, 4, 6) and number of groups of lines[47] (2, 3, 4, 5). Each map contained two horizontal lines and two vertical lines as well as one point that was the start or end point of three different lines. These maps are later referred to as M6, M8, M10 and M12 according to the number of Tangible Reels they required. All points and lines were associated with a numerical label, ranging from 1 to 12. The first point to be placed was labelled with number 1, the second with number 2, etc. The same rule was applied to lines.

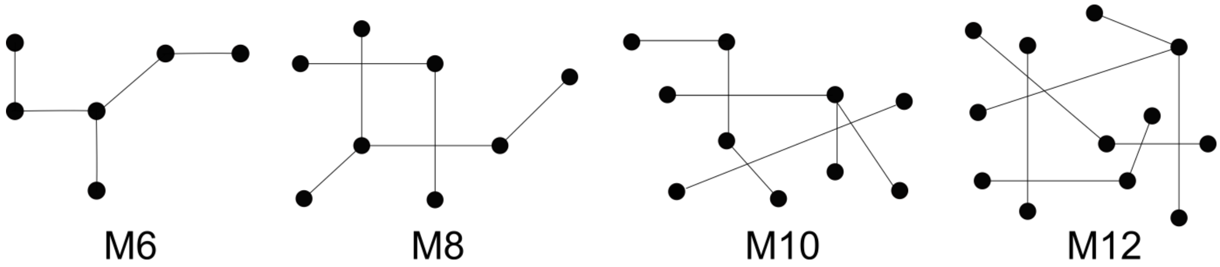

Figure 3.14. The four maps used for the evaluation. The maps are of increasing complexities and respectively required 6, 8, 10 and 12 Tangible Reels.

6.2.3 TASKS

For the construction, participants were asked to construct the map as quickly and as accurately as possible. When participants spent more than three minutes on one instruction, it was considered a failure, and we provided help so that they could continue. Otherwise, no help was provided during the construction.

For the exploration, participants had to answer three questions of this type: *what are the names of the two points at the extremities of <name of a line>?* They had to explore the map and select the appropriate line and points and give the name out loud. Even if they knew the answer, they were asked to find and select the object.

6.2.4 EXPERIMENTAL DESIGN

Maps were presented in the same order for all participants, from the simplest to the most complex, which ensured that participants had sufficient experience with the system when reconstructing the most complex maps. In fact, in order to keep the length of the experiment within two hours, the training phase was relatively short and only simple maps were reconstructed.

6.2.5 MEASURES

Usability was evaluated by measuring efficiency, effectiveness and satisfaction. Efficiency was assessed with three measures: 1) time needed to build the entire map; 2) time to place one object,

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[47] A group of lines is composed of several lines that can be consecutively built, by connecting the new Tangible Reels to the last Tangible Reel positioned. If the user must attach a new Tangible Reel to a Tangible Reel that is not the last one placed, then a new group is being started.

from the first construction instruction until the object was correctly placed; 3) time to answer each question. Effectiveness was assessed by the number of maps each participant successfully built, the number of Tangible Reels correctly placed and the number of correct answers to the questions. Satisfaction was measured using the SUS questionnaire and the participants' comments. During exploration, we logged for each question the number of elements selected by the users before finding the right answer. We therefore collected (6 TR + 8 TR + 10 TR + 12 TR) * 8 participants = 288 trials for the construction task, and 4 maps * 3 questions * 8 participants = 96 trials for the exploration task.

6.2.6 DATA ANALYSIS

As discussed in the introduction (Chapter 1, 7.3), and in accordance with the recent recommendations from the APA organization [73], we report effect sizes with 95% confidence intervals instead of p-value statistics based on the Null Hypothesis Significance Testing paradigm. To compute point estimates and 95% confidence intervals, we use the following methodology:

- For completion times, we first log-transform all completion times to correct for right skewness. We then compute means and 95% exact confidence intervals [138] on the transformed data and report the results anti-logged, i.e. we report geometric means instead of arithmetic means, as suggested in [266]. For pairwise comparisons, we first compute differences between means on log-transformed data, for each participant and each factor. We then compute means and 95% exact confidence intervals and report the results anti-logged: differences between mean completion times are therefore expressed as ratios [48,72] [48].
- For other variables, we compute means and 95% bootstrap confidence intervals [138]. For pairwise comparisons, we compute differences between means for each participant and each factor, and then compute means and 95% bootstrap confidence intervals [138].

6.2.7 PROCEDURE

The study consisted in one familiarization phase followed by the construction and exploration tasks. During familiarization, participants were told how to manipulate the Sucker pads, how to interpret audio instructions to construct a map, and how to explore it. They could practice as many times as they wanted to on a map composed of five points. After each construction, participants had to rate the difficulty of the task on a 7-point Likert scale. At the end of the session they answered the SUS and NASA-RTLX questionnaires, as well as the following question: *do you think that constructing the map helped you to understand it?* They were also invited to provide any comment on the system. Figure 3.15 summarizes the procedure.

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[48] For example, to compare the time needed to construct M8 vs M10, we first log all completion times. Then, for each participant, we compute the difference log(M10) – log(M8), yielding a total of *n* data points (*n* = number of participants). We then use these *n* data points to compute the mean difference and exact 95% CI. The results are reported anti-logged, and expressed as ratios (see http://www.jerrydallal.com/lhsp/ci_logs.htm, for example, for a detailed explanation–but the key point is that *log(x) - log(y) = log(x/y)*).

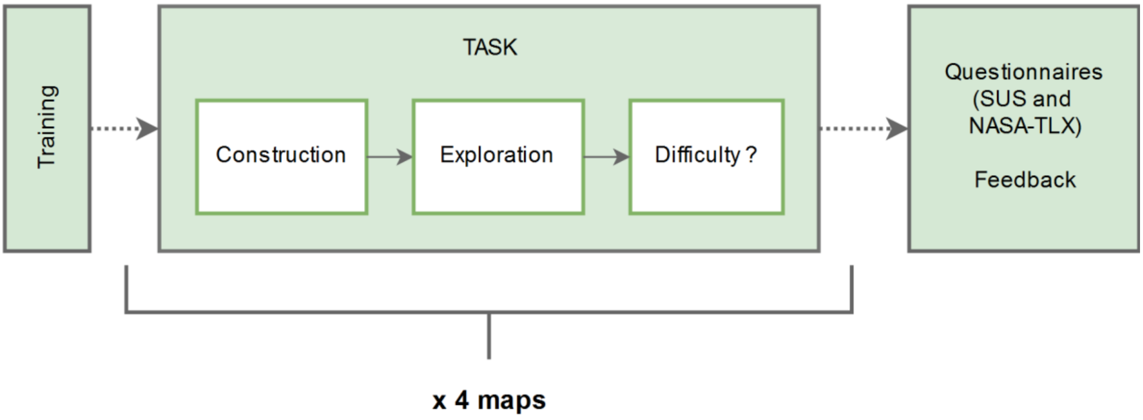

Figure 3.15. Procedure for the evaluation. Participants were first explained how to construct the maps. They then had to construct and explore four maps of increasing complexities. At the end of the session, they answered the SUS and NASA-RTLX questionnaires.

6.3 RESULTS

6.3.1 CONSTRUCTION

SUCCESS

A map was considered correct if the users managed to construct it without the help of the evaluator and if all the Tangible Reels were correctly connected to each other. Similarly, a Tangible Reel was considered to be correctly positioned if it was placed without the help of the evaluator and if it was correctly connected to the other objects.

Only 5 Sucker pads out of 288 were not correctly positioned or linked (98.3% correct). As there was one Sucker pad incorrectly positioned per map, 27 maps out of 32 were correct. Two maps were incorrect because one line did not start from the correct Sucker pad (M6, M12), and three maps were considered incorrect because the participants required assistance from the evaluator (M8, M12, M12). Because the number of errors was very low, we provide further details on each one:

- For Participant 2 (P2) in M6, the instruction "attached" was played before the user effectively attached the Sucker pad. By that time, the user had moved away and attached the Sucker pad to an incorrect one.
- P1 (on M12) pulled out a string too strongly and detached the Sucker pad. He then reattached it to the wrong Sucker pad.
- P3 (M12) spent several minutes trying to attach a Sucker pad to the point 9, whereas the instruction "attach an object to 8" was repeated several times.
- P8 experienced difficulties in focusing on the task: when placing one object on M10, he moved the extremity of the string instead of the Sucker pad, so that the guidance instructions remained unchanged.
- When constructing M12, P8 found the correct Sucker pad to attach, but did not wait long enough to hear the feedback ("attached"), and then tried to attach it to other Sucker pads.

COMPLETION TIMES

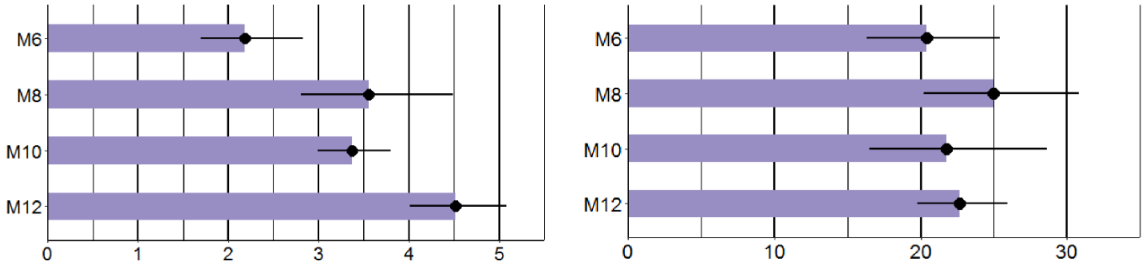

Figure 3.16. Left: Mean completion times to construct each map, in minutes (N = 8). Right: Mean completion times to place a Sucker pad, in seconds (N = 8). Error bars show 95% CIs.

Figure 3.16 (left) shows mean completion times to construct correct maps (not including the three maps constructed with the help of the evaluator). Figure 3.16 (right) shows the time needed to place a Tangible Reel, in seconds. The average time to place a Tangible Reel, computed across all maps, was *M* = 22.5 s, 95% CI [18.6, 27.2]. Pairwise comparisons, expressed as ratios between completion times, did not reveal strong differences: M6-M8: 1.2, 95% CI [1.0, 1.5][49]; M6-M10: 1.1, 95% CI [1.0, 1.2]; M6-M12: 1.1, 95% CI [1.0, 1.3]; M8-M10: 0.9, 95% CI [0.7, 1.0]; M8-M12: 0.9, 95% CI [0.8, 1.1]; M10-M12: 1.1, 95% CI [0.9, 1.2].

Three steps were required to place a Tangible Reel: 1) attaching it to a previous one or placing it anywhere on the table; 2) following rough guidance instructions; 3) following fine guidance instructions. The time needed to complete each action was computed for each condition (Figure 3.17). Results indicate that participants spent very little time following rough guidance instructions as compared to the other steps. In fact, participants spent 11.8% of the total time following rough guidance instructions (95% CI [10.5, 13.2]), 39.3% following fine guidance instructions (95% CI [37.1, 41.3]), and 48.9% attaching or placing a new Tangible Reel (95% CI [46.4, 52.2]). Pairwise comparisons, expressed as ratios between completion times, did not reveal reliable differences between the maps (see Figure 3.18).

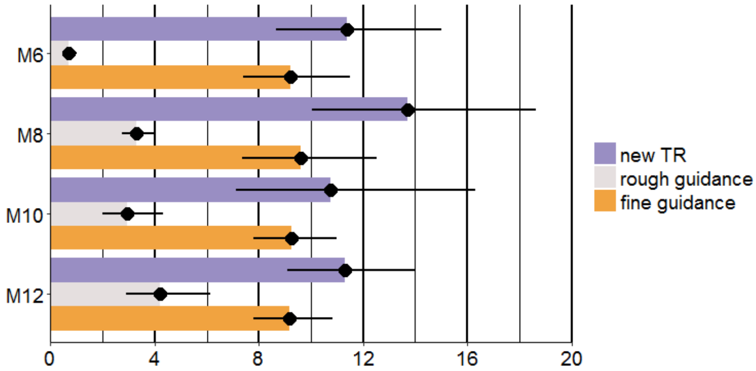

Figure 3.17. Mean times for the three steps required to correctly place a Tangible Reel, in seconds (N = 8): 1) attaching a Sucker pad to a previous one or placing it anywhere on the table (purple); 2) following rough guidance instructions (gray); 3) following fine guidance instructions (orange). Error bars show 95% CIs.

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[49] M6-M8: 1.2, 95% CI [1.0, 1.5] means that we compared M6 and M8 and that the ratio between completion times (M8/M6) was 1.2, 95% CI [1.0, 1.5].

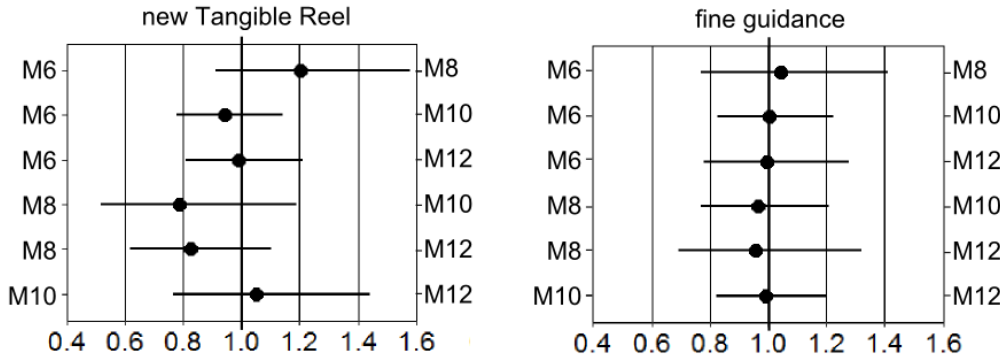

Figure 3.18. Mean ratios of completion times (right map / left map, N = 8). Values superior to one indicate the participants spent more time performing the step with the right map than with the left map. For example, the first line in the left figure indicates that the ratio M8/M6 is approximatively 1.2. Error bars show 95% CIs.

6.3.2 EXPLORATION

PERCENTAGE OF CORRECT ANSWERS

The percentages of correct answers to the exploration questions were: 91.7 for M6 (95% CI [75.0, 95.8]); 95.8% for M8 (95% CI [79.2, 100.0]); 91.7% for M10 (95% CI [75.0, 95.3]), and 79.2% for M12 (95% CI [54.2, 87.5]). Errors were due to the fact that: 1) participants pointed to the right intersection but followed the wrong line (P2 twice, P3, P6); 2) maps were incorrectly constructed (P1, P2); 3) Sucker pads got detached, creating a misalignment between the tangible map and the digital map (P8 twice); 4) participants had trouble correctly performing the pointing gestures and therefore to select the lines (P3, P6).

COMPLETION TIMES

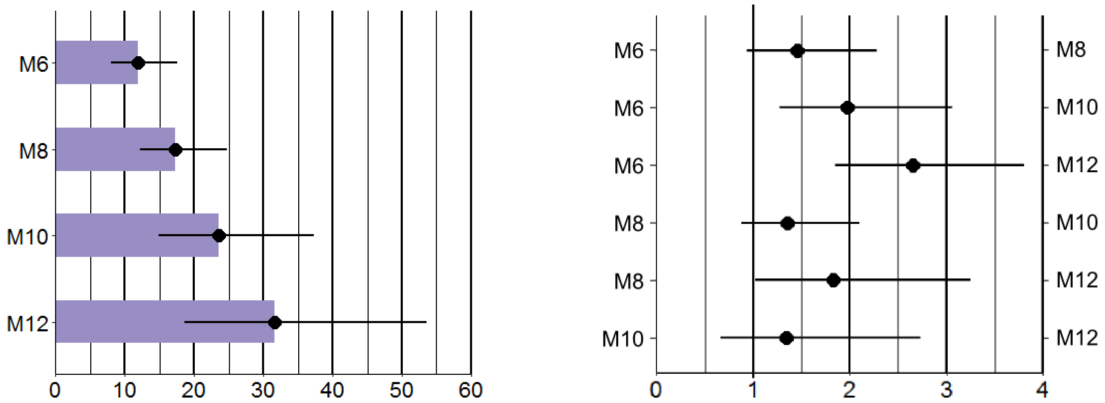

Figure 3.19. Left: mean completion times to answer one question per map, in seconds (N = 8). Right: mean ratios between completion times (right map / left map, N = 8). Values superior to one indicate the participants spent more time answering the question with the right map than with the left map Error bars show 95% CIs.

Figure 3.19 (left) illustrates completion times to answer one question (for correct answers only). It shows that the time needed to answer the questions tended to increase with the complexity of the maps. Pairwise comparisons, expressed as ratios between completions times, are shown in Figure 3.19 (right). Participants took reliably longer to answer the questions with M12 than with M6 (almost three times longer) and M8. Completion times were also reliably longer for M10 as compared to M6 (about two times longer).

NUMBER OF ELEMENTS SELECTED

Table 3.4 indicates the average number of points and lines selected by the users to answer each question, in each condition (correct answers only). As the complexity of the maps increased, participants tended to select more elements before finding the correct answer.

Table 3.4. Mean number of elements selected per question, per map (N = 8).

Map	Number of elements
M6	3.9 95% CI [3.4, 4.4]
M8	6.0 95% CI [5.3, 7.4]
M10	7.4 95% CI [5.7, 9.1]
M12	8.1 95% CI [6.6, 9.8]

6.3.3 QUESTIONNAIRES

The average SUS score for the system was 82.19 (95% IC [72.3, 90.6]). Participants had to rate the difficulty of the task on a 7-point Likert scale (1 = very easy; 7 = very difficult). Figure 3.20 (left) illustrates the number of participants who found the task rather easy (1, 2), average (3, 4, 5) or difficult (6, 7). Figure 3.20 (right) reports the scores of the NASA-RTLX questionnaire.

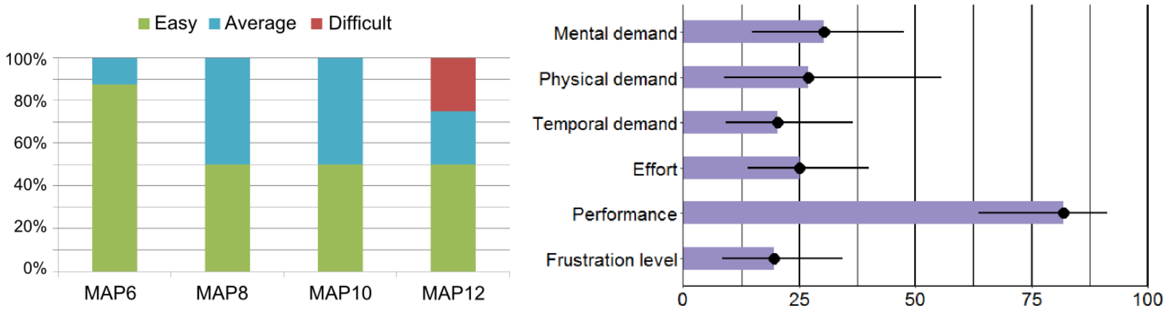

Figure 3.20. Left: For each map, number of participants who found the task easy (green), average (blue), or difficult (red). Right: Mean scores for each dimension of the NASA-RTLX questionnaire (N = 8). Error bars show 95% bootstrap CIs.

6.4 DISCUSSION

6.4.1 CONSTRUCTION

Results show that most of the participants managed to construct the maps without experiencing any usability issues. Only five maps were not correctly constructed and the most complex map was constructed in approximatively four minutes. The rough guidance technique allowed the users to quickly move a Sucker pad close to the target and hence proved to be efficient. On average it was three times longer to follow fine than rough guidance instructions, which suggests that the overall completion time could be reduced by improving the fine guidance mode. Most of the participants found the instructions easy to understand. P4 stated that "instructions are extremely clear, it is impossible to make mistakes" and similar comments were made by P1, P2, P3, P6. However, P3 and P5 declared that at the end of the experiment they were getting tired, notably because it was necessary to remain concentrated (P3 said that she failed in reconstructing M12 because she felt like she "couldn't hear the instructions anymore"). Similarly, we observed that P4 failed in constructing M10 and M12 because he stopped focusing on the instructions.

6.4.2 EXPLORATION

89.6% of the answers were correct, which shows that the system is usable to retrieve specific spatial information. However, we observed two issues: 1) some participants had difficulties in performing pointing gestures with one finger only, and did not always manage to select the lines and points quickly. For example, P3 kept using several fingers and spent on average 9 seconds to select one element, whereas P7, who perfectly understood the gesture, spent only 1 second per element; 2) some participants pointed at the intersections of two lines and therefore did not always manage to select the line they wanted to. It should be mentioned that the digital representation was not perfectly aligned with the tangible representation because two different systems of coordinates were used (one for the camera placed below the tabletop and the other for the infrared frame). We addressed this issue in a revised version of the prototype (see 7.1).

6.4.3 COMPLEXITY

Four participants found that difficulty remained similar in the last three conditions, i.e. for M8, M10 and M12 (P1, P2, P4, and P5) or in the last two conditions, i.e. for M10 and M12 (P4 and P7). The two participants who failed at reconstructing M12 found this map difficult. P1 and P5 stated that it became difficult to attach two Tangible Reels together when they were already close to other Tangible Reels. Two subjects (P4 and P7) declared that it would be too difficult to understand and explore more complex maps. It is interesting to note that the completion times to place one object did not significantly increased with the map complexity, neither the number of usability issues. Three failures (in M10, M12 and M12) were likely due to a lack of concentration that could either result from the length of the experiment (these conditions happened at the end of the experiment) or from the complexity of the map per se.

Overall, we did not observe any reliable difference between the times to construct oblique, vertical or horizontal lines. However, we observed that the time to place an object anywhere on the table after hearing the "new object" instruction (i.e. an object that must not be linked to a previous one) gradually increased as the map was being constructed. This probably reflects the time needed to find the space needed to place a new Sucker pad, suggesting that the complexity of the maps that can be built is limited by physical constraints (number and size of Tangible Reels) rather than by the user's ability to interpret audio instructions and perform appropriate actions.

6.4.4 SATISFACTION AND USEFULNESS

Overall, participants were highly satisfied with their performance (the score for the "performance" item of the NASA-TLX was superior to 66% for 85% of the participants), and found the system usable, as indicated by the SUS score. Six participants mentioned that they were able to understand the maps after constructing them, and two pointed out that it would have been easier if they were explicitly asked to understand and memorize the maps. Finally, three participants said that the system would be very helpful for educational purposes (mathematics and Orientation & Mobility lessons).

Based on these comments, we decided to investigate the potential benefits of Tangible Reels for learning activities and organized an educational workshop with visually impaired students, whose observations are described in the following section.

7 EDUCATIONAL WORKSHOP

Together with Laurence Boulade, a teacher working at the IJA, we set up a two hours educational workshop at the IRIT with the Tangible Reels. Three pupils from one of the teacher's classes were present. One pupil could only perceive very bright stimuli; the second pupil had low vision. Besides this visual impairment, the child suffers from serious hearing disability and autistic symptoms are present (mainly a lack of concentration). A third pupil with low vision had recently entered the IJA and also attended the session.

7.1 ADDITIONAL FEATURES

For this workshop two additional features were developed: the possibility to replace the name associated to each Tangible Reel by a vocal message recorded by the users themselves; the possibility to construct a map without being guided and then to save this map for later use. We also improved the application by applying a homography[50] to camera images.

7.1.1 ANNOTATION

When reflecting upon the workshop we thought that allowing the pupils to record and then replay their voice would be a good way to make them more engaged and interested in the application. Besides, this functionality had already been discussed with Laurence Boulade during my Masters project in order to design new pedagogical activities such as recording personal stories to better remember names or places. Voice and sound recordings have also been successfully used for a design probe evaluated by IJA students in the framework of AccessiMap [28].

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[50] https://en.wikipedia.org/wiki/Homography_(computer_vision)

We therefore implemented an additional functionality that enables users to annotate the map. Once the map is reconstructed a wooden cube can be placed next to any object (points or lines) to select it. Only the nearest object is selected. To start and stop the recording we used a Wizard of Oz procedure[51]. When the voice command "begin" was given a key was pressed in order to start the recording. Another key was pressed to stop the recording. During the exploration the recorded annotations are played instead of the original names. It is possible to indicate which student is annotating the map so that only the annotations recorded by a particular student are played (however, this feature was not used during the workshop).

7.1.2 CONSTRUCTION

Being able to draw a map or part of a map is a skill that students must acquire throughout their schooling. For Laurence Boulade it is also a way to check that a map has been correctly understood. Drawing the map is also a quick way for the teacher to create a digital map. We therefore developed a new application that enables a user to construct a graphic using Tangible Reels, with the possibility of annotating it, and to save the coordinates of each point as well as the links existing between certain points. In this way a student can reconstruct a map that has been drawn by another student (in order to learn it or correct it for example).

For this feature users must first construct the map. Then, they indicate which points are linked together. At present this feature has not been entirely implemented and needs to be done manually by clicking on the camera image with the mouse. However, this functionality could be easily implemented and improved.

7.1.3 HOMOGRAPHY

As we said earlier, the algorithm we used to match the coordinates given by the TopCode library to the one given by the infrared frame was not efficient enough. For the second version of the Tangible Reels application we applied a homography to each tag's coordinates provided by the TopCode library. To do so we translated into Java a C++ application called LIMACE, developed and provided by Alain Crouzil, a researcher at IRIT to whom we are very grateful for his help and availability. By applying this homography, we achieved a very high precision between the digital map, the tangible representation and the multitouch frame. In this way, selecting an object was easier and fewer errors were observed.

7.2 ORGANIZATION

For this workshop we used the same set-up as described above and completed it with a microphone (for the voice recordings) and several chairs upon which the pupils could stand. In addition to the additional features previously described, we increased the delay between vocal instructions. No other changes were made.

The workshop was organized as follows: pupils were invited to observe and touch the table in order to apprehend its size and understand how it operates. Various tasks were then performed

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[51] This functionality was fully implemented after the workshop: when the cube is turned upside down a "beep" sound is played, indicating the beginning of the recording. The recording stops when the cube is once again turned upside down.

by the pupils, simultaneously or alternately: attaching and detaching a sucker pad; connecting two objects together; placing one object by following the guidance instructions; constructing a line; retrieving the names of points and lines, etc. Afterwards, and depending on the pupils, several graphics were reconstructed. Eventually each pupil reconstructed the map of France, sometimes collaborating with others. They were then shown how to record a name and spent the rest of the session annotating the six main cities of France (see Figure 3.21).

Figure 3.21. One pupil interacting with the map of France built with six Tangible Reels.

7.3 OBSERVATIONS AND FEEDBACK

7.3.1 USABILITY

Both pupil and teacher feedback was highly positive, and this was confirmed by our observations. Firstly, the three pupils were able to manipulate the Tangible Reels and construct lines after only a few minutes. By the end of the session it was no longer necessary to remind them of the presence of the small extension for detaching a Sucker Pad. They only experienced some difficulties to attach the Sucker Pad while they were following the guidance instructions, but were able to detach it by themselves and continue the task.

Secondly, the three pupils managed to correctly interpret the guidance and construction instructions and were able to correctly place a Tangible Reel after a couple of trials. This is because it took them a little time to understand that they had to move the Tangible Reels more slowly when the fine guidance instructions are given. The frequency for the guidance instructions was even too slow for the older pupil, who had to wait before each instruction. We turned off the sound several times in order to give some explanations or additional help without being disturbed by the repeated instructions. This suggests that a "pause" command could be provided to improve the system usability.

Similarly to what we observed during the evaluation, the pointing gesture used for the exploration led to some usability issues. One child in particular could barely reach the upper part of the table because of his height, which made it very difficult for him to point vertically at objects located on the other side of the table. However, by the end of the session, we noticed that pupils tended to exaggerate the gesture by lifting their finger far above the table before selecting an object, which reduced the number of unsuccessful selections.

As for the « annotation cube », it has been greatly appreciated by the pupils who quickly understood how they needed to manipulate it to start or stop the voice recording. However, because sometimes the three pupils worked on the same map, vocal annotations were replaced. It will be interesting to provide each pupil with a personal cube so that while working on the same map each child could register their own voice recordings and listen to them by placing their cube in a specific place on the table (to "filter" the annotations to be played).

7.3.2 LEARNING BY DOING

From the very beginning of the workshop the two youngest children seemed very pleased to play with the Tangible Reels and their comments were positive. For example, when one pupil was placing a Tangible Reel, the other one would often ask whether he could do it afterwards. However, the third and oldest pupil got very quickly "bored" because he found the task too easy and also because it was "always the same thing"–we did reconstruct the same line several times. Only when he reconstructed a more complex representation did his interest slightly increase, especially when the teacher congratulated him for doing it very quickly.

However, when the children were introduced with the "annotation" feature, they all became more engaged and interested. They all expressed their wish to annotate all of the cities and enjoyed listening to their own voice. We also started working on the map of France at the same time, which further increased the motivation and engagement of the youngest pupils because they wanted to show their teacher that they could remember the map. As for the older pupil, he made a point showing the teacher that he could correctly and quickly memorize the six cities that he did not know before, by annotating them several times.

We also observed that for one child placing the Tangible Reel was like a game. He expressed positive emotions every time he heard the feedback "found". However, because he sometimes moved the Tangible Reels too quickly, guidance instructions would start again, which made him express disappointment. As for the pupil with autistic symptoms, the teacher noted that he had stayed much more focused on the activity than he usually does when working on non-interactive maps.

Finally, the teacher reported that constructing the map was certainly beneficial in terms of learning because of the proprioceptive feedback inherent to the process of physically reconstructing the map.

8 GENERAL DISCUSSION AND PERSPECTIVES

With the Tangible Reels project, we aimed at designing a tangible interface that would enable visually impaired users to independently construct and explore tangible maps. We envisioned that our interface could replace or at least complement existing tools (corkboard and magnetic board) that are low-cost, easy to make and easy to manipulate but are non-interactive and cannot be used without the help of a sighted person. Even though these tools cannot be used to display as much information as tactile maps, they can be updated and open various perspectives in terms of applications (reconstruction, annotation, etc.) and learning. Based on the quantitative and qualitative results from the two evaluations and the educational workshop that we conducted, we address in this section the four research questions that we listed in 1.3 and, when possible, suggest improvements or lines of thought for further research. In the last section we particularly discuss shape-changing perspectives for Tangible Reels.

8.1 DESIGNING TANGIBLE OBJECTS

The design of tangible objects for visually impaired users had only been partially addressed in the literature. In fact, in the few cases where the design had been evaluated, results were mixed and issues of stability were reported. Besides, the proposed tangible objects could only be used to make digital points physical. In this project we contributed to this question by designing tangible objects that are stable and can also be used to make digital lines physical.

Two designs were proposed and evaluated: the Weights and the Sucker Pads. In terms of stability, the preliminary study indicated that both types were stable. However, the height of the Weights sometimes hindered the exploration process and some participants found that they could more easily be knocked over. Because of the tension applied by retractable reels the Weights could not be smaller as a minimum amount of lead had to be placed inside them. However, if lines are not essential, it could be possible to design lighter and therefore smaller Weights that could be used, for example, in combination with Sucker Pads. As for the Sucker pads, although they need to be regularly cleaned (as well as the glass table) and cannot be used on non-flat surfaces, they proved efficient for the Tangible Reels interface and could certainly be adapted to other tangible interfaces.

The main limitation of the Sucker Pads is their size (around 4 cm wide), which is partially due to the fact that the Tangible Reels were made "by hand" with off-the-shelf products. The manufacture of specifically adapted sucker pads could reduce their size. For example, Tuna Knobs[52] are tangible knobs that can be used by DJs to efficiently interact with a touch screen; they are composed of a sucker pad and are relatively small (3 cm diameter). Also, we were able to track small markers because we did not use a projection foil. However, this prevents the development of applications where visual feedback could be beneficial, for example for users with low vision or for collaborative interfaces with blind and sighted users. There is therefore a need to develop tangible tabletop interfaces that could support the tracking of small markers while enabling rear-projection. In that sense, the use of infrared LEDs embedded in the tangible objects is particularly promising (see [217] for example). In Appendix D, we report on the first steps of

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[52] http://www.tunadjgear.com/

the design of small tangible objects composed of LEDs and that could be embedded into Tangible Reels (and particularly into Weights).

In terms of construction, the two evaluations and the educational workshop indicate that the Tangible Reels are easy to manipulate, even by children, and that no particular training is required. Magnets appeared as a good design choice to connect two Tangible Reels and could be considered for other tangible objects for visually impaired users. Similarly, the use of retractable reels enabled users to quickly and easily construct lines of varying lengths. Observations from the educational workshop indicate that having physical lines was beneficial in terms of (mental) representations: children would follow them with their hands to identify the overall shape of the constructed map, as they would do with traditional raised-line maps.

8.2 INTERACTION TECHNIQUES FOR THE CONSTRUCTION AND EXPLORATION OF MAPS

In order to be accessible without the help of a sighted person, tangible maps need to be reconstructed by the users themselves (or by the system, see Chapter 5). In existing works, the design of suitable interaction techniques to guide the user during the reconstruction process has not been addressed. We contributed to this question by designing a two-step guidance technique as well as by proposing a procedure for the reconstruction of tangible maps with Tangible Reels, based on audio instructions.

Both the second evaluation and the educational workshop proved that these techniques were efficient and could be easily mastered after a couple of trials only. In the evaluation, 98% of the Tangible Reels were correctly placed by the users, without the help of a sighted person. Similar performances were observed even with the most complex maps. However, results also suggested that the two-step guidance technique could be improved, and especially the fine guidance phase that was relatively longer than the rough guidance phase. For example, the frequency at which the fine guidance instructions were given could be adjusted, as well as the instructions themselves. Nevertheless, we believe that this technique could be adapted to other tangible interfaces requiring a visually impaired user to quickly and accurately place an object in its right place.

Despite the fact that the majority of exploration questions were correctly answered, the proposed interaction technique for the exploration was not as efficient as the interaction techniques for the construction. In fact, due to the hardware used (an infrared frame) a specific pointing gesture had to be used, which appeared to be difficult to perform for some users. For the educational workshop, an improvement had been made to the system by implementing a homographic correction, making it easier and more efficient to combine the pieces of information received by the infrared frame and the camera. Although it led to fewer errors, the pointing gesture was still difficult to perform, especially for the children. Identifying and tracking fingers is a key challenge in the design of interactive tabletops and several approaches have been proposed in the literature, mainly based on computer vision algorithms (e.g. [164]). With this in mind, we suggest that a more robust algorithm could be used to better identify gestures performed within an infrared frame: in addition to making the selection of a Tangible Reel easier, such an algorithm could also be used to enhance the exploration. For example, touching a line with one or two fingers could result in the system playing two different pieces of information.

The educational workshop was an opportunity to investigate additional features. In particular, we proposed an interaction technique for the vocal annotation of the map. This functionality was greatly appreciated by the children and the teacher and opened new perspectives for pedagogical activities with the Tangible Reels interface. For example, giving each child an "annotating tool" could enable several pupils to collaborate around the same physical map while being able to customize their own digital map. In the context of the advent of crowdsourced geospatial data (e.g. [252]), such a tool could also be used to annotate a map with pieces of information concerning accessibility (for example to indicate whether a building is accessible or to warn other users about transitory obstacles such as roadworks). We also proposed a "drawing" tool that enables users to construct their own maps and save them so that they can later be reconstructed by themselves or by other users. Even though we did not fully implement this functionality, we believe that it also opens new perspectives in terms of education and collaboration. For example, a visually impaired user could draw a map, annotate it and make it available to other users that could reconstruct and explore it and, in turn, edit it (physically and/or with vocal annotations).

The main limitation of the Tangible Reels interface is that, at the moment, it does not enable the users to quickly switch between construction and exploration modes: the map is first constructed, and then explored. Although the above mentioned functionalities (annotation and construction) could make the application less sequential, future work is required to provide the users with an effective way to switch between these modes. In that sense, the design of tangible menus could be beneficial. It will also be interesting to implement additional functionalities that would enable the user to select which pieces of information to display (the user will therefore be guided to display or hide particular points of interest).

8.3 REPRESENTATION

The number of Tangible Reels that can be placed above the table limits the complexity of the map. In addition, although most of the participants managed to construct the more complex maps, some reported that the task was difficult when objects were too close to each other. However, participants managed to construct maps composed of twelve Tangible Reels and several lines that were intersecting one another. Therefore, using Tangible Reels, it is possible to construct parts of metro maps and overview maps. The maps that we used for the evaluation were not composed of individual points. By combining Sucker Pads to display lines and smaller Weights to display points of interest only (as suggested previously in 8.1), other types of maps could certainly be designed.

As we discussed in the previous section, advanced interaction techniques could also enhance the types of maps represented. For example, when a larger amount of information is required, it would be interesting to physically render the most important elements using Tangible Reels, and then provide access to less important elements using gestural interactions as well as audio or haptic feedback (see [241] for instance). Areas could also be represented and conveyed through audio (see [283] for example and Figure 3.22, left) or illusory tactile textures [96]. We also developed an alternative version of the interface that supports the construction of "closed" shapes by indicating to the user how to join the start and end points of the shape. Finally, the Tangible Reels themselves could be augmented to support the construction of more complex representations. For example, in order to construct curves, small objects could be attached to the strings in order to bend them (Figure 3.22, middle). Also, some Tangible Reels could be equipped with double retractable reels and serve as "crossing points" from where several lines could be constructed (Figure 3.22, right).

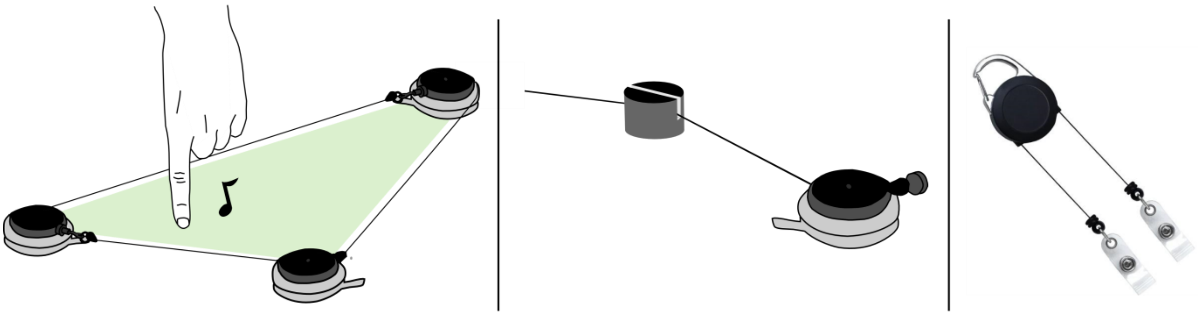

Figure 3.22. Three possible improvements for Tangible Reels. Left: areas could be conveyed through audio. Middle: additional objects could be used to construct curves. Right: double retractable reels could increase the number of lines (retrieved from http://www.retractablereels.com/double-carabiner-badge-reel-black-p-747).

Because Tangible Reels can be used to make digital points and lines tangible, they can obviously be used to construct diagrams based on these two graphical primitives, as shown in Figure 3.23.

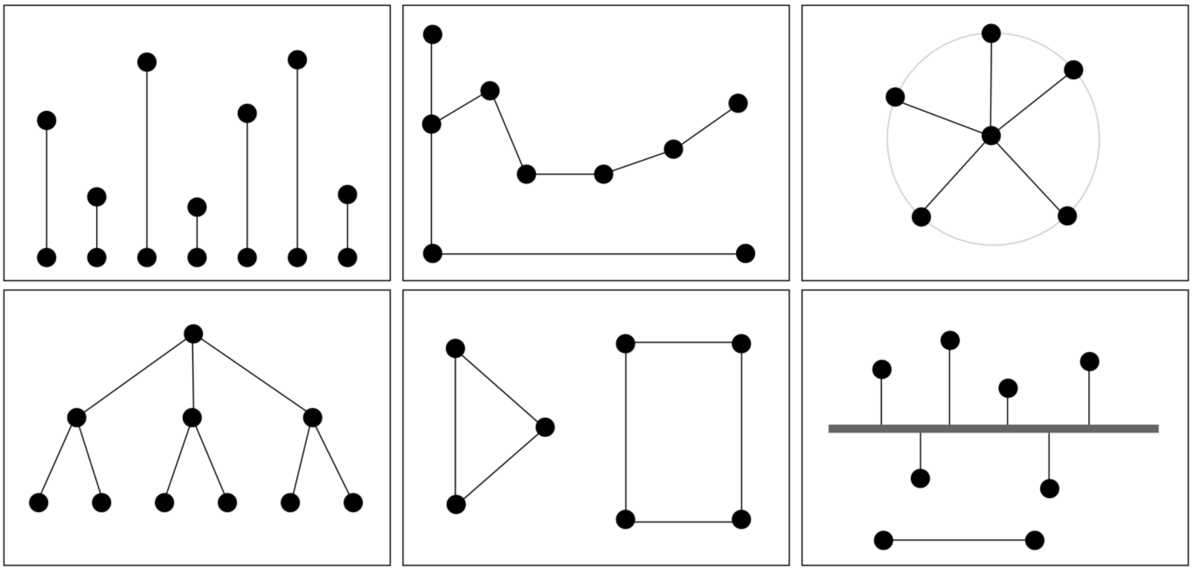

Figure 3.23. Examples of diagrams that could be constructed with Tangible Reels. Proportions between the size of the working area and the size of the Tangible Reels have been preserved. From left to right and top to bottom: bar charts; line graphs; pie charts; organigrams, workflow diagrams or mind maps; geometrical shapes; timelines (the gray rectangle represents a metallic bar that could be fix upon the table to provide a stable frame of reference).

8.4 UNDERSTANDING TANGIBLE MAPS AND LEARNING BY DOING

When designing the Tangible Reels interface, we wanted to ensure that users would be able to understand the maps. Results from the preliminary study indicate that participants were able to reproduce maps previously built by the evaluator, even when several lines intersected with each other. Therefore, maps built with Tangible Reels appeared to be understandable. Additional exploration features such as those previously mentioned could certainly help users better understand and memorize the maps.

In addition, both the second evaluation and the educational workshop indicated that constructing the map can be helpful in terms of learning and also in terms of engagement. Such observations are in line with "the more general view within education that hands-on activity or manipulation of physical manipulatives can be of particular educational benefit" [188]. Future work might specifically consider comparing the acquisition of spatial knowledge of tangible maps depending on whether the user actively reconstructs them or not (see Chapter 6, 3.1).

8.5 TOWARDS ACTUATED TANGIBLE REELS

In the framework of a CHI Workshop entitled Shape-Changing User Interfaces, we discussed how the dynamicity of maps built with Tangible Reels could be enhanced by actuating them, and proposed three design ideas. The first part of this section is a simplified version of the article submitted for the workshop. The second part illustrates how existing research projects on "Cord UIs" could further improve the design of Tangible Reels.

8.5.1 SCENARIO: COMPARING THE RESULTS OF REGIONAL ELECTIONS

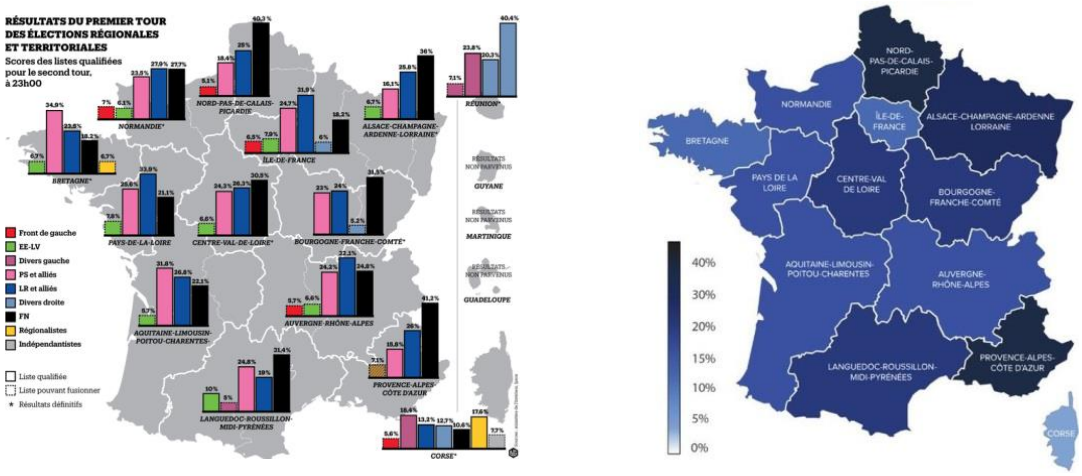

Figure 3.24. Examples of geostatistical maps. Left: this map of France presents the result of regional elections; bar charts are displayed in each region to indicate the percentage of the vote for the main political parties. Retrieved from *Libération*, 07/12/2015. Right: this map of France presents the score of a single political party; the darker the region, the higher the score. Retrieved from www.lexpress.fr/actualite/politique/elections.

In December 2015 regional elections took place in France. Results were very often presented with (interactive) visual maps, inaccessible to visually impaired users (e.g. Figure 3.24). In the following sections we describe how, in the future, a visually impaired user could explore these results on a map, thanks to actuated Tangible Reels. First, the user could zoom in on his/her region (*design example #1: zooming and panning*). The user could then select a town in order to display on a dynamic bar chart the scores of the main political parties for the selected town (*design example #2: dynamic bar charts*). Finally, the user could return to the map of France and explore the score of his/her favorite political party in the main cities of France (*design example #3: height-adjustable Tangible Reels*).

DESIGN EXAMPLE #1: ZOOMING AND PANNING WITH ACTUATED TANGIBLE REELS

Tangible Reels enable visually impaired users to render digital spatial configurations tangible, but zooming and panning operations have not yet been implemented. To achieve this, the Tangible Reels could be equipped with a motor so that they could move independently towards a specific direction. When the users want to update the map they could move two objects apart (zoom) or one object only (pan); all the remaining Tangible Reels would then move to their new positions, allowing the user to quickly rescale or reposition the map. Such an interface would be less expensive than a raised-pin display and would allow users to work on a larger surface. Building on this idea, we later investigated the use of small robots to give visually impaired users access to "pan & zoom" maps (Chapter 5).

DESIGN EXAMPLE #2: DYNAMIC BAR CHARTS WITH TANGIBLE REELS

Figure 3.24 is an example of a map presenting election results that would likely be transcribed onto a table in order to be accessible to visually impaired users. In section 8.3, we indicated that Tangible Reels could be very useful in constructing bar charts, especially if they were actuated, because the bar chart could refresh/reshape itself. In the framework of our scenario users could select a town by double-tapping on a Tangible Reel. They will then be asked to place new Tangible Reels beside the map, on a separate working area. These Tangible Reels could therefore move in order to form a bar chart, which could update itself when the user selects another city. This type of physical visualizations could enable visually impaired users to quickly gain an overview of the graph and, if several bar charts were used, to easily compare two areas whose values could be displayed simultaneously. Building on this idea, we later developed an actuated bar chart, which is described in Chapter 5.

DESIGN EXAMPLE #3: HEIGHT-ADJUSTABLE TANGIBLE REELS

In Figure 3.24 a sighted user can quickly identify regions with the highest score of a particular political party. For visually impaired users sonification techniques could be used but will force the users to explore the map sequentially, raising mnemonic and cognitive issues. We envision than Tangible Reels could be composed of a height-adjustable part that could be moved up or down (Figure 3.25), similarly to HATs [199]. Therefore one could place a Tangible Reel on each area of the map and its height would be adjusted according to the corresponding value (the higher the Tangible Reel, the higher the score of the party in that city). Such an interface would allow visually impaired users to quickly identify areas where the party performed best, simply by sweeping their hands above the map and detecting the highest Tangible Reels.

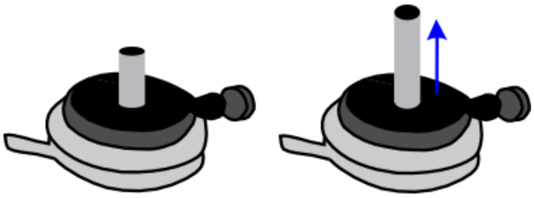

Figure 3.25. A height-adjustable part could be added to the Tangible Reels to convey quantitative information.

8.5.2 CORD USER INTERFACES

The term “cord UIs” has been used by Shoessler et al. [273] to describe “sensorial augmented cords that allow for simple metaphor-rich interactions”. In their article the authors proposed five prototypes that enable users to interact with their devices’ cables, including lamps, hard drive and headphones. The idea is to augment the cables with sensors that can detect when the user touches the cable in a particular way (sliding, pinching, twisting, swinging, stretching or kinking) or adds an object to the cable (such as a clip). Knots can also be detected and different commands can be triggered depending on how tight or where the knot is. Although limited, research on actuated cords has shown the potential of using strings or cords as input commands (see [16,146,240] for examples of input devices composed of a retractable reel). For example, in [90] a cord is used to draw and manipulate curves on a screen; several gestures such as snapping, twisting or pushing can be detected and triggers different commands. It would be interesting to investigate how these input techniques could be adapted to the Tangible Reels.

Furthermore, we found during informal tests that putting a vibrator motor at one extremity of the string made the entire string vibrate. We believe that different patterns of vibrations could greatly enhance the Tangible Reels. For example, the vibrations could convey different meanings such as the nature of the link that exists between two elements (similar to tactile lines that can be solid, dashed or dotted) or a direction (similar to arrows). Making the string vibrate could also draw the attention of the users towards a particular line, e.g. when they are searching for it or when the line is incorrectly built.

9 CONCLUSION OF CHAPTER 2

In this chapter, we described the design, implementation and evaluation of a tabletop TUI that enables visually impaired users to independently construct and explore tangible maps, using a new type of tangible object called Tangible Reels. Tangible Reels are composed of a sucker pad that ensures stability, with a retractable reel that renders digital lines tangible. In order to construct a map, audio instructions guide the user to precisely place Tangible Reels onto the table and create links between them. During subsequent exploration, the device provides the names of the points and lines that the user touches. A pre-study confirmed that Tangible Reels are stable and easy to manipulate, and that visually impaired users can understand maps that are built with them. A follow-up experiment validated that the designed system, including non-visual interactions, enables visually impaired participants to quickly build and explore maps of various complexities. Finally, an educational workshop confirmed that both the interface and the Tangible Reels can be quickly mastered, even by young children. This workshop was also an opportunity to assess the usefulness of two additional features (vocal annotation and construction). We also illustrated how Tangible Reels could be used for the (re)construction, exploration and manipulation of different types of diagrams, including charts, geometrical shapes or timelines. Finally, we identified several ways the Tangible Reels could be improved to allow for a richer experience, notably by actuating them, as well as additional functionalities that could take advantage of the flexibility of the interface (e.g. adding or removing Tangible Reels to display particular points of interest). In the following chapter, we further investigate the use of tabletop tangible maps and diagrams for educational purposes and propose another solution to increase the expressiveness of tabletop TUIs for visually impaired users.

CHAPTER 4

THE TANGIBLE BOX: TANGIBLE AND TACTILE GRAPHICS FOR LEARNING ACTIVITIES

> *C'est dans cet esprit que j'ai pris la décision d'entreprendre une campagne d'information, de renseigner, faire voir, me faire comprendre. Ce fut une résolution immense, qui n'a rien changé du tout, mais ce fut très important pour la résolution, qui est une grande vertu.*
>
> Romain Gary (Emile Ajar). Gros-Câlin.

Chapter structure

1 INTRODUCTION

1.1 MOTIVATIONS AND RELATED WORK

TUIs have a strong potential to enhance learning, by making the participants more engaged, fostering collaboration or supporting learning-by-doing and hands-on activities. Despite a vast amount of research work on the benefits of TUIs to support learning for sighted students, there has been very little work on the benefits of TUIs for visually impaired students, mainly because of a lack of accessible TUIs–an issue that we discussed in Chapter 2, Part E. We think that the technical solutions as well as the interaction techniques and feedback that we proposed in the previous chapter, as part of the development of the Tangible Reels prototype, could serve as a starting point for the design of TUIs for visually impaired students. However, the Tangible Reels, like most TUIs, rely on a set-up that is somewhat bulky and takes up space. Besides, as stated in the discussion section, one limitation of this prototype was the impossibility to rely on visual feedback as we used a transparent glass. The size of the Tangible Reels also makes it necessary to use a relatively large surface, which limits the type of environments where the interface can be installed.

If TUIs are to be used in specialized educational centers, they must be low-cost and easy to install and calibrate (or, ideally, do not require any calibration at all). In addition, they should be as compact as possible so that several teachers may have a device at their disposal, instead of having a single device shared between different groups of students or teachers. They should also be adapted to a large range of users who might have different visual impairments (blind or low-vision) and ages (children, teenagers, etc.). Another important aspect is the range of learning activities that a TUI used within a specialized educational center should support. Although specifically designing a TUI for a particular activity and a particular subject such as geometry or geography can be interesting, notably concerning the affordance of the tangible objects, it also means that teachers will need to develop and own several TUIs whenever they want to investigate the use of tangible interaction for a particular project. Such an approach raises issues in terms of storage, but also in terms of cost, time and skills required to develop and implement each new interface.

A number of projects have been conducted to facilitate the deployment of affordable and compact tabletop TUIs, based on various approaches: using daily objects (e.g. [186]), projecting images on non-interactive surfaces (e.g. [271]), tracking fingers with a camera instead of a touch-enabled device, placing the camera above the surface for tracking objects and fingers instead of below to prevent the need of using dedicated surfaces, etc. Wilson [341] summarized the main advantages and disadvantages of existing technologies for tabletop TUIs. As we described in Chapter 2, Part D, 3, one common approach is to place a camera above the tabletop, usually by hanging it on a shelf or on the ceiling. According to Wilson [341], the main disadvantages of this approach are the following: the installation is difficult and requires special hardware; once the camera is installed, it is not possible to use the TUI in a different place; calibration must be done regularly to compensate for the camera's potential movements; user's heads, arms and body can occlude the camera's field of view. Innovative solutions have been proposed to reduce issues concerning the installation and calibration of the set-up, such as integrating the camera into a lamp that can be placed on any surface [245] or using a smartphone's or tablet's integrated camera (e.g. Osmo[53]), but occlusions cannot be avoided. Although "there has been no systematic analysis of the true impact of such occlusions" [341], systems that rely on a camera placed above the tabletop may not be the most appropriate for visually impaired users, who, unlike sighted users, cannot see whenever their hands or head is occluding one tangible object and therefore cannot move their hands or head in consequence.

The second most common approach is to place a camera below the tabletop. Wilson [341] indicated that this approach results in set-ups that are difficult to construct, do not allow users to put their legs under the table, provide only a limited resolution because a diffuser surface is often used, require a dedicated surface, and, overall, "present manufacturing and distribution problems for a real product". As we already discussed, such set-ups are particularly limited by the projector's throw (if an image is to be projected) or by the camera's focal length [274]. Other approaches include commercialized interactive tabletops, which are expensive, or touch-enabled devices, including tablets, which are limited in size. Multitouch screens are an interesting alternative but do not inherently support object tracking and so dedicated tangible objects must therefore be designed (e.g. [210]). Also, affordable technologies for tracking such objects usually rely on computer vision algorithms that identify "footprints", which make it necessary for the objects to be relatively large. In addition, techniques and/or technologies to ensure the stability of this type of tangible object have not been investigated.

To compensate for these limitations, Wilson introduced PlayAnyWhere [341], a compact and self-contained tabletop system that can project images onto any surface and track fingers and objects. Instead of being placed above or below a tabletop, both the camera and the projector are embedded into a single device that is "sitting off to the side of the active surface". Instead of tracking the fingers themselves, their shadows are analyzed, making it possible for the system to detect pointing gestures (one finger per hand). However, the system did not prevent occlusions and, like all systems that rely on computer vision algorithms, was dependent on lighting conditions.

On the basis that there is a shortage of self-contained and low-cost TUIs, we aimed to design and implement a TUI for visually impaired students that would fulfill, as much as possible, the criteria listed above. By developing such a TUI, we aim to provide a platform that could be used by teachers to diversify the range of educational activities proposed to their students, but also by researchers to specifically investigate the benefits of educational activities that are based on the manipulation of tangible objects in (collaborative) learning for visually impaired students.

1.2 RESEARCH QUESTIONS

Taking into account these considerations, this project was driven by the following research questions:

- **How to design a low-cost, self-contained and portable TUI for visually impaired students?** To date, there is a lack of research concerning the development of TUIs that could be used within specialized educational centers for visually impaired students. In

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[53] https://www.playosmo.com/en/coding/

addition to practical constraints (e.g. installation and calibration), some constraints must be taken into account for the TUI to be adapted to visually impaired users, namely the stability of the tangible representation and the fact that the TUI cannot solely rely on visual feedback to enhance the tangible representation.

- **How to support different learning activities for a variety of subjects and users?** If the TUI is to be used by different teachers, it must support various learning activities as well as various types of graphical representations. Therefore the TUI should not be overly specific but should instead provide a generic set of tangible objects that could be adapted to several activities, subjects and users.
- **What is the design space of learning activities supported by the proposed TUI?** So far, we mainly investigated how a TUI could be used to enable users to reconstruct a map or a diagram, even though we also provided an initial investigation of interaction techniques for two other tasks (construction and annotation). With this project, we aim to further investigate the design space of tasks that can be supported by tabletop tangible maps and diagrams.

1.3 CHAPTER STRUCTURE

This chapter is organized as follows. Firstly, we provide in section 2 a detailed description of the Tangible Box–the prototype that we developed–along with reasons why specific technical choices were made. In section 3, we describe the implementation of the prototype, in terms of hardware and software. In section 4, we report ideas suggested by five specialized teachers with whom we organized participatory design sessions. Based on these ideas, we provide a framework for the design of learning activities supported by the Tangible Box. In section 5, we describe in detail three applications. Finally, we discuss in section 6 the benefits and limitations of the Tangible Box, before describing a number of perspectives to improve and enhance this interface.

2 DESIGN RATIONALE

To fulfill the aforementioned criteria, a number of choices were made concerning the design of the Tangible Box, which is illustrated in Figure 4.1. In this section, we specify the design rationale of the different elements of the interface and, in each sub-section, discuss the benefits and drawbacks of the design choices that we made.

2.1 USING STABLE TANGIBLE OBJECTS THAT CANNOT BE OCCLUDED

In the previous chapter, we reviewed various techniques that have been considered to make tangible objects stable. We notably relied on the work of Hennecke et al. [99] who investigated different approaches including magnets, glue, electro-adhesion and vacuum-based adhesion. When designing the Tangible Reels, we tested various solutions based on glue and electro-adhesion, and none of them proved satisfactory. Vacuum-based adhesion was successfully used for the design of the Sucker Pads, but requires sucker pads that must be used on glass surfaces only and that are too large to be used on a surface of moderate size, which is an important criterion if the TUI is to be portable.

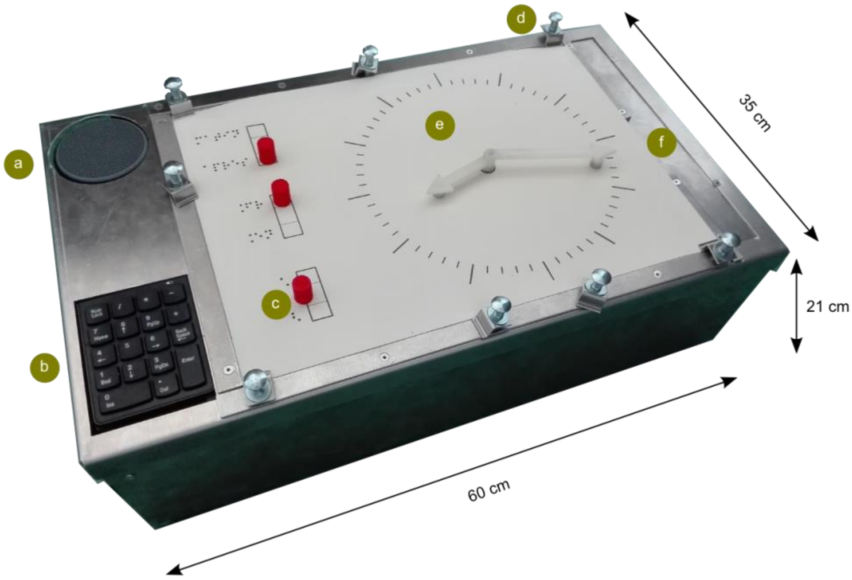

Figure 4.1. Overview of the Tangible Box. a) speaker; b) keyboard; c) a tangible object, composed of two parts (one above the surface, in red, and one below the surface); d) one element of the fastening system that holds the supports in place; e) support used for the activity (here, a raised-line clock); f) dedicated area where unused tangible objects can be placed.

In this project, we decided to investigate the use of magnets as a way to make tangible objects stable. However, because one requirement was to track the tangible objects using a camera placed below the tabletop (to avoid occlusions), it was not possible to simply place magnets on top of a magnetic board, as it is not a transparent surface. We therefore decided to use two magnets for each tangible object: one is placed above the surface and can be manipulated by the user; the other is magnetically attached to the first one, on the other side of the interaction surface, i.e. below the surface (Figure 4.2). Whenever the user moves the upper magnet, the lower magnet moves with it. By affixing a tag under the lower magnet, a camera placed below the tabletop can track it and, indirectly, track the upper magnet.

The main advantage of these objects is that they are very stable and that the user cannot occlude them as the tag is fixed under the bottom magnet, which is under the surface and therefore unreachable. Also, they are very easy to assemble and are low-cost (the magnets we used cost 0.30 € each). The main disadvantage is that once an object is placed on the table, it cannot be lifted and needs to be slid over the surface to stay connected with its paired magnet. Although this obviously restricts the design space of interaction, it ensures the stability of the tangible representation while making it possible to easily move the objects. Another issue is that if the user lifts the upper magnet, the lower magnet becomes detached. To prevent this from happening, a magnetic sheet is glued under the surface: therefore, even if an upper magnet is removed, the corresponding lower magnet does not detach, as it is held by the magnetic sheet.

Figure 4.2. Each tangible object is composed of two parts, magnetically attached together. Left: the surface is between the two parts. Middle: 3D-printed objects with magnets inside. Right: view from below: a colored tag is affixed under the lower magnet for tracking and a magnetic sheet is glued (in white) to prevent an object from becoming detached.

2.2 SUPPORTING MULTIPLE GRAPHICAL REPRESENTATIONS, TASKS AND DOMAINS

In Chapter 2, Part B, we described various materials that are currently used within specialized educational centers: these materials allow different types of activities, depending on whether they are static (raised-line, embossed or swell maps and diagrams) or updatable (German film and cork, magnet of self-adhesive boards). In addition, they are used for various subjects, including mathematics, geography, Orientation & Mobility, etc. Also, static tactile graphics can be used to represent any type of graphical representation and they remain the best way to make relatively complex graphical representations accessible to visually impaired users. Based on these observations, we investigated whether the tangible objects that we designed could be used in combination with different supports. By doing so, we not only aimed to adapt to current practices, but also to enhance traditional supports by making them interactive using tangible interactions, while at the same time building on their advantages.

Firstly, the tangible objects can be placed above and slide along **static tactile graphics** (e.g. raised-lines and swell graphics), without being blocked by the tactile elements. In addition, users can still feel when they are moving a tangible object across a tactile element. The main advantage of using static graphics is related to the principle of division of functionality [196], which specifies that “fixed information should be represented by immovable physical objects” and “directly manipulated data should be represented by [tangible objects]”. Using static tactile graphics with tangible objects, it is possible to represent fixed and complex information (such as grids or a country’s boundary) on the graphic while updatable and simpler information (such as data points or cities) is represented by tangible objects. By doing so, the complexity of the tangible representation can be greatly enhanced, and the static and traditional surfaces made interactive and updatable. Similarly, **thin 3D-printed** graphical representations such as the maps developed by Götzelmann [86] can be used.

The Tangible Box also supports the use of **German film**. The magnets are strong enough to stay attached even if an additional and thick surface is used, such as the drawing mat that is usually placed below German film. If the German film is used by the students themselves, the Tangible Box can support interactive drawing activities where the tangible objects serve as tools, for example to measure distances between two points or to annotate a drawing. The tangible objects can also be used as tokens: similar to the example we gave for the static graphics, it is possible to use a sheet of German paper onto which a grid has been printed and to ask the students to place a set of data points to create and possibly edit a graph. The German film can also be used by the teachers themselves in order to quickly create an interactive worksheet.

Whether it is with static graphics, 3D-printed graphics or German film, low-vision students are provided with visual feedback. However, if the device is to be used by students with moderate low-vision only, tactile feedback may be unnecessary. In that case, it is possible to simply use the Tangible Box with **regular paper**, or, for more updatable surfaces, with **whiteboard sheets**.

Finally, the Tangible Box can be used with **"ad-hoc" surfaces**, i.e. surfaces designed for a particular activity and that can be 3D-printed or made out of different materials. For example, a wooden piece can be placed above the tabletop and temporarily attached with Blu-Tack to represent a tangible timeline around which students have to place different tangible objects that represent a particular event. Such "ad-hoc" surfaces, or tactile guides, can also be used to delineate different working areas, restrict where the students can place or move the tangible objects, reduce the size of the surface, etc.

To adapt to these various supports, which can be of different sizes and thicknesses, a fastening system has been designed, which we describe in detail in section 3.1.2. It allows teachers and students to easily place a support on top of the Tangible Box.

2.3 INPUT DEVICES AND AUDIO OUTPUT

Users can interact with the system by moving the tangible objects. In particular, for each application, it is possible to use one object as a selection tool: whenever this object is placed next to another object, the piece of information associated with it is read (e.g. its name, its description, its corresponding value, etc.). In addition, a numeric keypad is placed on top of the Tangible Box and enables students to easily interact with the system (to switch from one mode to another, to trigger a particular command, to select the application to be launched, etc.). Concerning output, audio feedback is provided by a speaker embedded into the Tangible Box, and the volume can be adjusted by the users themselves.

2.4 SUPPORTING PORTABILITY AND EASY CALIBRATION

The camera used for tracking the tangible objects must capture the whole surface from below, which may result in the interface being too high to be portable and practical, as the camera must be placed at a sufficient distance. To tackle this issue, two solutions were considered: using a system of mirrors or using a wide-angle lens. Although using a mirror is efficient to reduce the height of the tangible box, it requires the camera to be placed sufficiently far from the mirror, and therefore makes the interface larger than necessary. We therefore opted for a wide-angle lens (170°), which reduced the required distance to less than 15 cm. With this solution, the final height of the Tangible box is 21 cm, which is significantly less than common tabletop TUIs that use a camera placed below the tabletop.

In addition, to make the interface relatively low-cost, self-contained and portable, the Tangible Box does not require a laptop: it relies on a Raspberry Pi, which is a small, lightweight and affordable single-board computer. This makes it possible to embed it together with the other pieces of hardware into a single box, hence the name of the prototype. In addition, all the pieces of hardware, and notably the camera, are firmly attached so that the Tangible Box can be moved without damaging the components. Concerning the objects, those that are not used can be placed on a dedicated part of the tabletop and do not need to be removed and stored elsewhere. For similar reasons, the fastening system that holds the different surfaces in place does not include any element that can be removed, and consequently lost.

As for the calibration, which is required for the camera to correct the image (see 3.2), the procedure needs to be performed only once because the camera is permanently fixed; hence, the calibration parameters are always the same. In addition, to avoid any issue with lighting conditions, the Tangible Box is opaque and a LED string light is placed inside the box. This ensures that the entire surface is evenly and sufficiently illuminated, which facilitates object tracking. Altogether, this makes the Tangible Box easy to install and to store. In fact, to set up the Tangible Box, the only action necessary is plugging it in, which turns on both the Raspberry Pi and the LED string light.

2.5 ADAPTING THE TANGIBLE BOX TO DIFFERENT USERS

The Tangible Box relies on the different elements that we just described. However, we also considered various ways in which the Tangible Box could be adapted to different users, notably by customizing the tangible objects or by allowing different input and output techniques.

2.5.1 3D-PRINTED HATS

Because the Tangible Box is meant to support a large range of applications, the tangible objects were designed to be as generic as possible. However, it is possible to customize them by covering the upper magnet with a 3D-printed "hat": each hat can have a particular width, height, shape, texture and even color, depending on what the tangible object is used for and by whom. This possibility offers numerous advantages. Firstly, having a way to tactilely identify each object can be useful, especially for blind users. Also, young children may be more engaged if they use tangible objects that have been customized and that can represent a monument, an animal, a shape, etc. For example, in the framework of the AccessiMap project, the MapSense [28] prototype was augmented with a set of fourteen tangibles that could be used on top of a tactile map: some represented a car, a monument, a flag, etc.; others could be filled with scents, such as olive oil or honey. Children's impressions were very positive. In addition, for students whose fine motor skills are not fully developed, it is possible to design 3D-printed hats that make it easier to grasp the tangible objects (see Figure 4.2, left, for example).

2.5.2 INPUT: VOICE COMMANDS AND KEYBOARD

Although it requires additional (but not expensive) hardware, the Tangible Box is compliant with two additional input techniques. Firstly, it is possible to plug in a USB microphone to enable students to interact with the Tangible Box using voice commands, an input technique that visually impaired users are used to, especially with their smartphone. Another possible input technique is to replace or complement the numeric keypad by a regular keyboard, therefore allowing users to interact with the Tangible Box in a more natural way, as well as to input text, for example to annotate a map or a diagram. To support these devices, two USB ports are available on one side of the box.

2.5.3 OUTPUT: VISUAL FEEDBACK

Similarly, although it requires additional (and more expensive) hardware, it is possible to connect an external monitor to provide dynamic visual feedback to low-vision users (students and teachers), and, possibly, to their sighted peers. Although a monitor can be relatively expensive, most classrooms are now equipped with at least one monitor or projector that could be temporarily used with the Tangible Box, preventing the need to buy a new one. To support this option, an HDMI port is available on one side of the box. It is also possible to use a laptop to directly access the Raspberry Pi's Desktop over a private network via a remote desktop application and a Wifi router placed inside the box.

3 IMPLEMENTATION

In this section, we describe both the hardware and software of the Tangible Box. For the hardware, a few schematics are provided in Appendix B[54]. The cost of the elements is also given in Appendix B (the Tangible Box costs approximatively 280 €).

3.1 HARDWARE

3.1.1 TANGIBLE OBJECTS AND 3D-PRINTED HATS

Each tangible object is composed of two neodymium circular magnets, 8 mm diameter, 4 mm high and with a magnetic strength of ~2 kg[55]. The 3D-printed hats have been made with an Ultimaker 2+ printer. To prevent two magnets under the surface from attaching to each other, each lower magnet is embedded into a 3D-printed circular object, 25 mm diameter and 7 mm high.

3.1.2 FASTENING SYSTEM

The fastening system (Figure 4.3) is designed to adapt to supports of different sizes and thicknesses. It is composed of eight holding elements placed at the periphery of the interactive surface (Figure 4.1). These elements are composed of a screw which holds in place a spring-loaded metal plate that applies pressure on the support. Only four elements out of the eight are required to hold a given support in place. The four elements actually used depend on the size and ratio of the support. When not in use, elements are rotated by 90° so that the metal plate is lifted off the support. To change the support, all elements are rotated and lifted off: this simplifies the manual operations required to replace and adjust a support on the interaction surface. Once the support is in place, the four appropriate elements are rotated. The pressure applied by the metal plates can be adjusted by turning a screw, but this is generally not needed as the spring mechanism adapts to a large range of support thicknesses.

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[54] .stl files can be downloaded here: https://github.com/julieducasse/tangiblebox

[55] More precisely, we use ring magnets; when the Tangible Box is used with a sheet of German paper, students can place the tip of the pen inside the magnet to leave a mark.

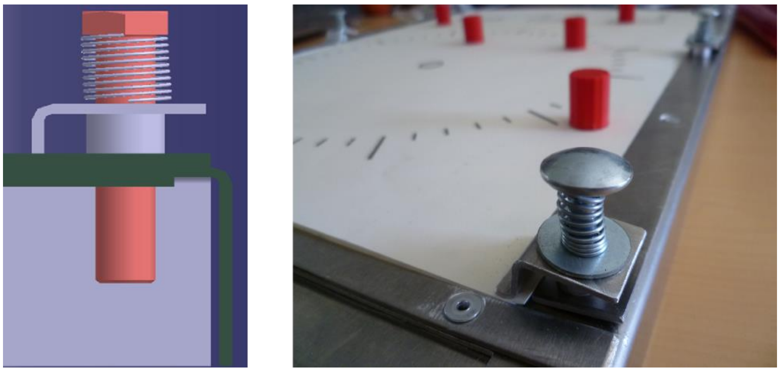

Figure 4.3. Fastening system, to adapt to a large range of support thicknesses.

3.1.3 BOX

To ensure the strength, lightness and affordability of the Tangible Box, the box is made out of a 1 cm thick aluminum plate, bent by a press brake. The Tangible Box is composed of two parts: the base (i.e. the bottom and sides of the box), and the lid. Therefore, it is possible to easily access the elements inside the box for maintenance purposes. To help users correctly place the different surfaces, a part of the lid is slightly recessed. The lid is also composed of two slots, for the speaker and the numeric keypad. On one side of the box, notches allow access to the USB and HDMI ports. Overall, the Tangible Box is 60 cm long, 35 cm wide, 21 cm high.

3.1.4 INSIDE AND ON TOP OF THE BOX

A circular speaker is placed on top of the box, as well as a numeric keyboard. The following elements are placed inside the box (Figure 4.4, right): 1) a Raspberry PI into which the PiCamera, keyboard and router are plugged, as well as two USB extenders and one HDMI/VGA extender (to plug in additional input or output devices); 2) a PiCamera (resolution: 2592 × 1944, fisheye lens - FOV 170°), which is attached to the Rapsberry Pi; 3) a Wifi router; 4) a LED string light; 5) an extension socket into which the Raspberry, LED string light and speaker are plugged. Supports have been 3D-printed (Figure 4.4, left) for the Rapsberry, PiCamera, speaker, keyboard, LED string light and router to hold them in place.

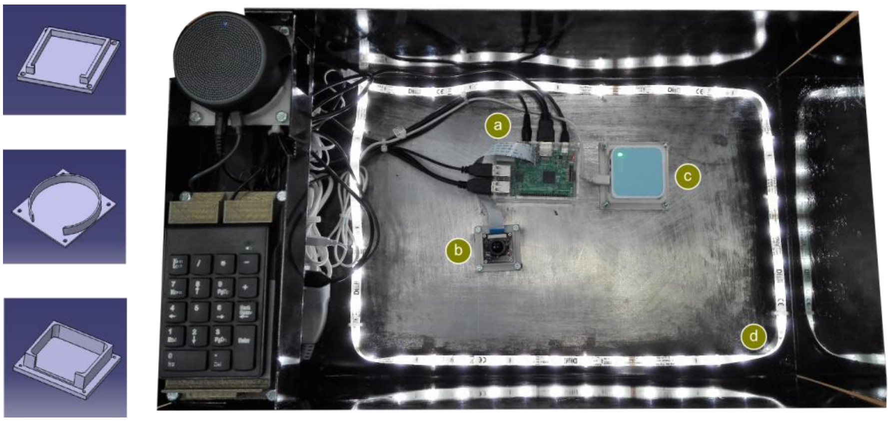

Figure 4.4. Inside the Tangible Box. Left: 3D-printed supports for the router, speaker and camera. Right: a) Raspberry; b) PiCamera; c) router; d) LED string light.

3.2 SOFTWARE

Because the PiCamera is a wide-angle camera, there is a fish-eye distortion in the image. To correct the image, the intrinsic and extrinsic parameters of the camera were first computed from several views of a calibration pattern, using OpenCV and Python. Due to these required rectifications, the efficient resolution is limited and is not enough to track fiducials. We therefore chose to track tags of different colors and shapes, therefore taking advantage of the fact that the inside of the box is evenly illuminated by the LED string light and is not sensitive to external lighting conditions. We first threshold the image, along different HSV values, and then extract the contours to identify the shape of the tags. Each object is associated with a unique combination of one color and one shape, making it possible to track several objects.

Audio feedback is provided with the Pico TTS engine and the Pico2Wave library. Applications were developed with Python 2.7.

4 DESIGNING APPLICATIONS FOR THE TANGIBLE BOX

In order to gain a more comprehensive overview of which applications would be worth developing, we conducted participatory design sessions with specialized teachers. In this section, we first report the main findings of these sessions, before introducing a framework for the Tangible Box, whose aim is to facilitate the design (and development) of applications for the Tangible Box.

4.1 PARTICIPATORY DESIGN SESSIONS

At the very beginning of the project, we set up a meeting with one mathematics teacher to collect initial ideas about potential applications. Later on, we presented the current version of the prototype to four teachers in order to compile a list of applications that we could develop.

4.1.1 INTERVIEW WITH ONE SPECIALIZED MATHS TEACHER

The maths teacher mainly works with visually impaired middle-school students, and is also responsible for teaching visually impaired high-school students. On the basis that many maths exercises are inaccessible to blind students, as they consist of a set of questions about a graph (e.g. a bar chart), he proposed the following scenario. The teacher first "encodes" the graph into the application with a dedicated piece of software. Then, the students are guided to reconstruct the graph using vocal instructions (e.g. "go left, go right"). When the graph is reconstructed, the student can answer the questions.

A second scenario was proposed. A raised-line Cartesian plan is placed on the surface and students are asked to place tangible objects at specific coordinates (e.g. x = 2; y = 3). Depending on the chosen level of complexity, students can be guided, partially guided or not guided at all. They can also receive feedback (e.g. "x must be positive"). Then, they can check their answer with the system and, if the tangible objects are incorrectly placed, try again.

A third scenario was suggested, which relied on the use of a German film: the system helps the student to draw lines of different lengths and orientations by providing verbal instructions (e.g. "draw a point", "put your rule with the 0 below the point", etc."). Ideally, the application can be used with interactive measuring tools (e.g. protractors and rulers). At the end of the session, the student can take the sheet home or hand it in to the teacher.

4.1.2 BRAINSTORMING WITH FOUR SPECIALIZED TEACHERS

PROCEDURE AND PARTICIPANTS

We invited four teachers from the IJA to participate in a one-hour brainstorming session. One teacher (LB) was working exclusively with primary school children and teaches all subjects. The three other participants (FR, AC and DR) were working with high school students: FR and AC mainly teach mathematics; DR teaches English. LB and DR were already familiar with MapSense [28], an existing interactive tactile map prototype developed in the framework of the AccessiMap project, and used it for their lessons. As for FR and AC, it was their first participation in the AccessiMap project.

Participants were first explained the goal of the brainstorming session as well as how the Tangible Box works and what types of support can be used. In particular, we presented a non-interactive version of the Talking Clock prototype, which we describe in 5.1. Then, teachers were given 15 minutes to come up with various educational activities with the Tangible Box, individually. In the second part of the session, teachers were asked to describe their ideas to the other participants, who were free to comment or to suggest new activities.

SUMMARY OF PARTICIPANTS' IDEAS

An exhaustive list of the ideas proposed by the teachers is given in Appendix B. In this section, we provide a brief analysis of these ideas and report comments and ideas concerning the advantages and pitfalls of the Tangible Box.

Domains

The middle school teachers initially focused on their main teaching subject: FR and AC proposed several activities related to mathematics (and more precisely to trigonometry and Thales' theorem) and DR proposed one activity to help students discover and learn the boroughs of New York. The primary school teacher covered a larger range of subjects, including mathematics (algebra, graphs, metric units of mass, length, volume, etc.), geometry, history, geography and biology. Other participants found these ideas relevant, although they were not directly related to their main subject, and thereafter proposed additional ideas or improvements.

Activities

Two large categories of activities were proposed. Some activities relied on the use of a single tangible object that stands as a cursor and that the students move above the graphical representation to explore its different parts (e.g. the boroughs of New York, the chambers of the heart). The student can move the tangible object freely, or can be guided to follow a route, to trace the flow of blood, etc. The student can also be asked to follow a particular path and audio feedback is given if the student moves in the wrong direction (different types of guidance techniques were envisaged, based on more or less detailed verbal instructions or on sounds).

Other activities mainly relied on one or several tangible objects that represent a token that the student must position in its appropriate place (e.g. a city on a map, a historical figure on a timeline, an organ on a body parts chart, a point in the Cartesian plane). In that case, the system asks the students to place a particular object, and indicates whether the object is correctly placed or not. Once again, different levels of feedback were envisaged, depending on how "good" the answer is or on the student's age or abilities.

Other comments
For the two categories of activities, teachers planned to customize the tangible objects, although this feature had not been described in detail during the introduction of the session. For example, DR envisaged using a mini yellow cab for his activity on the boroughs of New York; FR suggested fixing Braille numbers on top of the tangible objects; LB proposed to 3D-print customized "hats" that will help students recognize historical figures.

In addition, three out of four teachers spontaneously mentioned how moving the objects physically could help students memorize their position, thanks to proprioceptive feedback provided by the physical displacement of the tangible objects. In particular, FR stated that moving an object along a line could be better than double-tapping on different points of this line, as is currently the case with MapSense. She also appreciated the possibility to place several objects on a map before asking for the system to check the representation, because the system can then give feedback on the correctness of the whole configuration (e.g. "you placed Paris below Toulouse" or "three elements out of five are misplaced: can you find them?") instead of providing feedback about one element only. Finally, the participants appreciated the fact that students could use the Tangible Box on their own, but they also expressed some concerns about the height of the box, which makes it a little bulky.

4.2 TANGIBLE BOX DESIGN FRAMEWORK

The participatory design sessions demonstrated that a large range of applications can be designed with the Tangible Box. However, we also observed that designing applications that take full advantage of the updatability of the graphical representations could be a little difficult for some teachers. This was probably due to the fact that most of them did not regularly use interactive prototypes in their class, and, needless to say, were not familiar with tangible interfaces. Therefore, a design framework for the Tangible Box could help teachers better apprehend the design space of applications for the Tangible Box and better identify which aspects they should take into account to design various applications, adapted to their student's needs, abilities and preferences. In addition, such a design framework can be very helpful to help teachers describe the applications they envisage, which can facilitate their implementation by providing a common frame of reference to communicate between teachers and software developers.

Based on the initial propositions of the teachers as well as our own ideas about possible applications, we propose a design framework composed of four themes: overall characteristics, material, activities and interactivity. Each theme is composed of a number of aspects that the teachers should consider when designing an application as well as by a couple of "hints" that summarize the main theme's concepts. Our aim is not to provide design guidelines, but rather to identify possible ways to create rich and diverse applications with the Tangible Box. The list of aspects that we discuss is not exhaustive, and is meant to be completed as new applications are developed.

4.2.1 OVERALL CHARACTERISTICS

This theme describes the main characteristics of the application, which include the **subject** covered, the **users' profile** (age, degree of blindness, etc.) and the **purpose** of the application. These pieces of information can, for example, help teachers decide if they need to design a single or several activities (e.g. to adapt to the students' skills), or if they need to design different types of feedback. This theme also includes information about the **graphical representation**: its type (e.g. a map) and its content. By authoring the content of the representation, it is possible to create applications of various complexities. For example, the three following aspects can be considered (the list is not exhaustive):

- Levels (single-level vs multi-level). Different pieces of information can be associated with one element to enhance the graphical representation (e.g. "1st level: Paris; 2nd level: Capital; 3rd level: 2.2 million inhabitants").
- Audience (individual vs collective). The digital representation can be the same for all students, or can be adapted to a particular student.
- Duration (ephemeral vs permanent). The digital representation (and notably vocal annotations) can be saved and used during another session. Also, the student can take the support home to revise (as proposed by the maths teacher with the German film).

Finally, the application can consist in one or several **activities**, which can be independent of one another (i.e. the user can choose any activity at any time) or dependent on one another (i.e. the user must first perform one activity, then the other, etc.).

- **Hint 1:** Adapt the application to different users, notably by designing several activities with various purposes, levels of complexities, feedback, etc.
- **Hint 2:** Consider using different contents for a single graphical representation (use different levels; customize the content for one student, etc.).
- **Hint 3:** If the digital representation is edited during one session, it may be interesting to provide a way to save it so that it can be loaded again for the next session.
- **Hint 4:** Consider allowing the student to take the support home.

4.2.2 MATERIAL

This theme describes the material required for the application. Firstly, different **supports** can be used (raised-line, swell, 3D-printed, "ad-hoc" graphics, etc.), as previously described. Secondly, a certain number of **tangible objects** can be used, which can be of various types: they can represent a piece of information and therefore represent a token (e.g. "Napoleon", "Eiffel Tower"); they can be used for construction purposes only (e.g. to hold the tangible representation in place); they can be used to interact with the application and therefore act as tools. In that case, different roles can be considered: for example, the object can be used to explore, select or edit another element (tangible, tactile or purely digital) or to select an item in a tangible menu.

Depending on the role(s) of the tangible objects, it is possible to vary their physical properties (height, shape, size), notably by customizing them with "hats". Finally, it is possible to make the tangible representation more expressive using additional **components** that do not need to be tracked by the system (see Figure 4.1 for example, where the hands of the clock are not tracked– only the objects at their extremity are).

- **Hint 5:** Keep in mind that any thin support can be used: raised-line graphics, German film, 3D-printed surfaces, photos, etc.
- **Hint 6:** To take full advantage of the Tangible Box, use several tangible objects.
- **Hint 7:** Consider having some tangible objects that represent the information, and other that the student can use to trigger commands, select an item in a menu, retrieve details about one element, etc.
- **Hint 8:** Use additional physical components to make the tangible representation more expressive.

4.2.3 ACTIVITIES

This theme details different types of activities that can be conducted with the Tangible Box. An activity can be seen as an "exercise", composed of a single task or of several tasks. Possible activities include (the list is not exhaustive):

- Exploratory activity. The aim of the activity is to let the student freely explore an existing representation by "carrying out manipulations or experiments and observing the results" [188].
- Expressive activity. The aim of the activity is to let the student "create an external representation of a domain, often on their own ideas and understanding" [188].
- Customization. The aim of the activity is to enable the student to customize an existing map or diagram, by editing or annotating it.
- Trial and error activity. In this type of activity, the student is asked to do something (e.g. move a tangible object to its right place). If it is not done properly, feedback is given and the student must repeat the procedure (until the task is correctly performed, or until the number of possible attempts is reached, etc.)
- Evaluation. In this type of activity, the student is again asked to do something but the system does not indicate whether the student is doing well or not. This type of activity can be useful for self-assessment, homework or tests.

To conduct these activities, a number of tasks must be performed by the student. Currently, the Tangible Box supports the following tasks:

- Exploration / Manipulation. The student retrieves pieces of information associated with the graphical representation. If the tangible representation is reconfigurable, the students can manipulate it.
- Annotation / Edition. The student annotates a particular element by recording a voice message or inputting text. If the tangible representation is reconfigurable, the student modifies the tangible representation in order to change the underlying model.
- Construction. The student constructs a graphical representation by manipulating the tangible objects, which can optionally be saved by the system.
- Reconstruction (with or without guidance). A digital representation is loaded and the student must manipulate the tangible objects in order to match the tangible representation with the digital one. The student can be (partially) guided or not guided at all. Different types of guidance can be envisaged by adjusting several parameters such as the units (centimeters, cells), the type of guidance (one or two steps), the type of instructions (e.g. "3 cm left, 5 cm up", "you are near/hot"), the modality (TTS or sounds).

- **Hint 9:** Depending on the application's purpose, consider different types of activities.
- **Hint 10:** For each activity, consider which task (or which set of tasks) is the most appropriate.
- **Hint 11:** If one activity is composed of a reconstruction task, consider different types of guidance instructions.

4.2.4 INTERACTIVITY

This theme lists possible input techniques and types of audio feedback, so that teachers can pick up which interaction technique and which feedback best fits the student's needs. As we already described, possible **input techniques** include: the numeric keypad (numbers, arrows, key "enter" to trigger a command, etc.), voice commands and tangible interaction. The following figures illustrate how users can interact with tangible menus, how they can interact with a single tangible object and how they can interact with an element of the support.

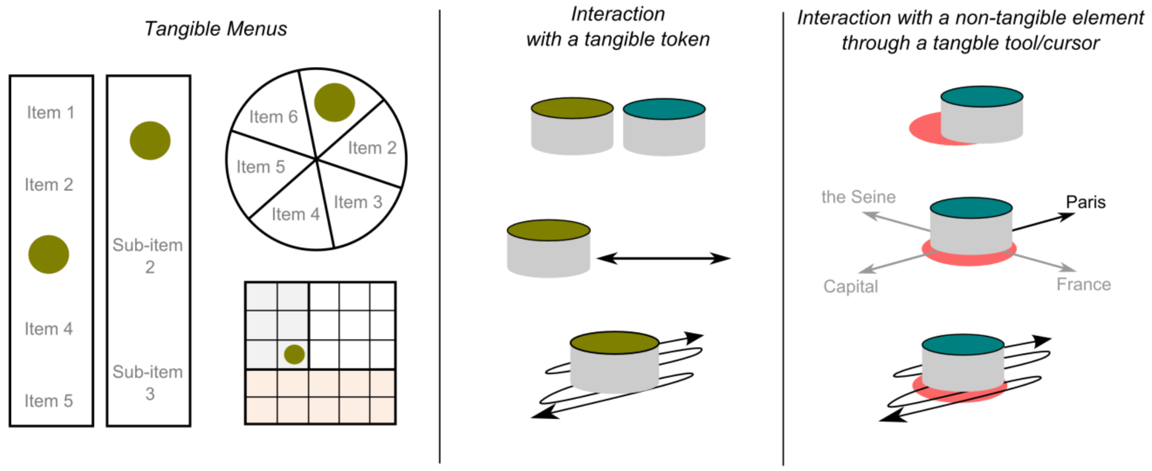

Figure 4.5. Tangible-based interactions. Left: selecting an item in a raised-line menu. Middle: retrieving the name of another tangible object. Right: retrieving the name of a non-tangible (but possibly tactile) element. The bottom figure in the middle and right columns indicate that the user must "shake" the element to reveal its content.

Audio feedback can be provided with sounds (e.g. *earcons* and *spearcons* [75]) or verbal messages. When a TTS is used, it is possible to vary its parameters in order to convey different pieces of information (e.g. the voice, the pitch and the speed). As we already discussed, it is also possible to connect a monitor to provide dynamic visual feedback.

- **Hint 12:** Consider using different input techniques (keyboard, voice commands or tangible interaction).
- **Hint 13:** Consider using different types of audio feedback (sounds, TTS).

4.2.5 SUMMARY

The following figure summarizes the main themes and aspects of the design framework. Once again, the lists of activities, tasks and tools that we provided are not exhaustive and will certainly be extended with the design of new applications. However, we believe that this framework is a good starting point to design, describe and improve applications for the Tangible Box. In addition to the list of hints, we provide in Appendix B a template for the design and description of applications, which can also serve as a starting point for developers.

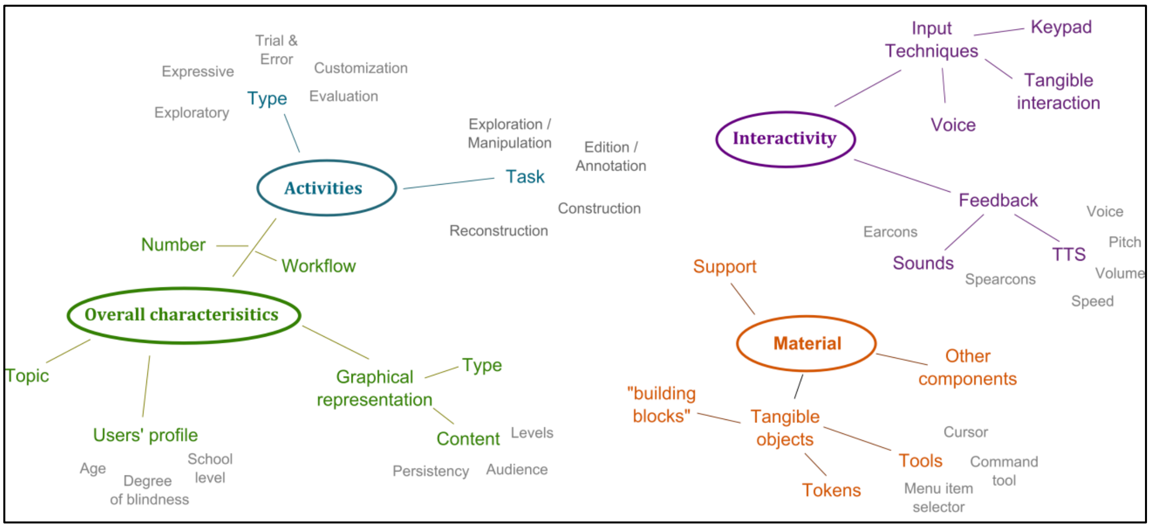

Figure 4.6. A summary of the design framework for Tangible Box applications, composed of four themes: overall characteristics, material, activities and interactivity.

5 EXAMPLES OF TANGIBLE BOX APPLICATIONS

In this section, we describe three applications for the Tangible Box. The first one, called the Talking Clock, was inspired by observations conducted at the IJA during the thesis. The two others are based on ideas given by the teachers during the brainstorming session. Up to now, a first version of the Tangible Clock has been implemented, and we plan to develop the other applications so that they can be used during the next school year. To describe the applications, we rely on the terms used in the design framework. In addition, for the first two applications, we propose a number of perspectives directly inspired by the framework, showing its potential to help teachers diversify their applications.

5.1 TALKING CLOCK

The Talking Clock application was designed for blind and low-vision students who are learning how to tell time in different ways (analogic: e.g. "it's twenty past two" vs digital: e.g. "it's two twenty") and/or in different languages (in French and in English). The application relies on a raised-line support showing clock ticks and delineating three menus. It is composed of two activities, which are not dependent on one another: users can select an activity using the "plus" and "minus" keys of the keypad. Two 3D-printed hands are used, as well as six tangible objects: two are placed at the extremities of the hands (tokens); one is a "building block" that holds the hands together (the center of the clock); three are used to interact with the three menus (tools). The first menu enables users to switch between a.m. and p.m. times; the second to switch between French and English; the third to switch between digital and analog ways of telling time.

The first activity is an exploratory activity during which the user is free to manipulate the hands (task: manipulation) and to select different modes using the tangible menus: the system reads out the time every five seconds (feedback: TTS). The second activity is a trial and error activity during which the user is asked to move the hands to indicate that it is a specific time (task: reconstruction). To check their answers, users must press the return key (input technique: keyboard): if the hands are correctly placed, another question is asked; otherwise, the system gives feedback and repeats the question (e.g. "The clock shows ten past three, but it must show ten past four. Try again!").

- Perspectives inspired by the design framework

To make the application accessible to young students, a very simple activity could be designed with the hour hand only, and without the menus. In addition to *exploratory* and *trial and error* activities, a *customization* activity could be designed, which would enable students to record voice messages concerning their timetable (e.g., at five o'clock: "school ends!"). These annotations could be saved (content: permanent), so that every time the students log into the application, they can listen to their timetable. For older students, an additional menu to select the day of the week could be added. Finally, in terms of feedback, the ticking of the clock could be played to make the students more engaged, as well as a bell sound for the hours (feedback: sounds).

5.2 TIMELINE

The application's purpose is for the teacher to check that students have a basic knowledge of historical periods. It is composed of a raised-line (or 3D-printed) timeline showing different periods (e.g. prehistory, Ancient Age, Medieval Age, Modern Age, Contemporary Age) and of a tangible pie menu with several items (e.g. historical figures, historical facts, artists, inventions, etc.). There is a tactile dot below each period. One tangible object is used as a cursor; five tangible objects represent a historical figure, fact, invention, etc.

We plan to develop a first version of the application composed of a single activity (*trial and error*). Users must first select an item from the menu. Then, the system assigns a piece of information, which depends on the menu item that was selected, to the five tangible objects and asks the student to place them in the appropriate period. The student can use the cursor to select each tangible object and to retrieve its name. Also, the cursor can be moved over the tactile cues to listen to a message giving a brief description of the corresponding period. Once the tangible objects are placed, the system indicates whether the answer is correct or not (e.g. "Homer and Rimbaud are not in their right place, try again!").

- Perspectives inspired by the design framework

To make the application accessible to a large range of students, an additional tangible menu could be used, which will allow them to select between different levels (e.g. easy, moderate, expert). Different types of activities could be envisaged, such as an exploratory activity (the user is guided to place the tangible objects in their right place and can then retrieve descriptions about the different elements of the timeline) or an expressive activity (students are provided with a blank timeline and can record a message for each time period and place the items where they want to). To make the application more playful, the tangible cursor could be replaced (or used in addition to) the "shaking" technique illustrated in Figure 4.5 and historical miniature figures could be printed and attached to the tangible objects.

5.3 TRIGONOMETRIC RATIOS

This application is for middle-school students who are learning trigonometric ratios, and relies on a sheet of German paper on which a line is drawn (representing the line between the numerator and denominator), as well as a set of right-angled triangles (drawn beforehand, by the teacher or, more interestingly, by the students[56]). It is composed of three activities, which are independent of one another: users can select an activity using the "plus" and "minus" keys. For all activities, three tangible objects represent the three vertices of the triangle (Figure 4.7): a Braille letter is glued on top of them (A, B or C). For the first activity, a fourth tangible object is used as a cursor; for the two other activities, three tangible objects represent the hypotenuse, the opposite side and the adjacent side of the triangle.

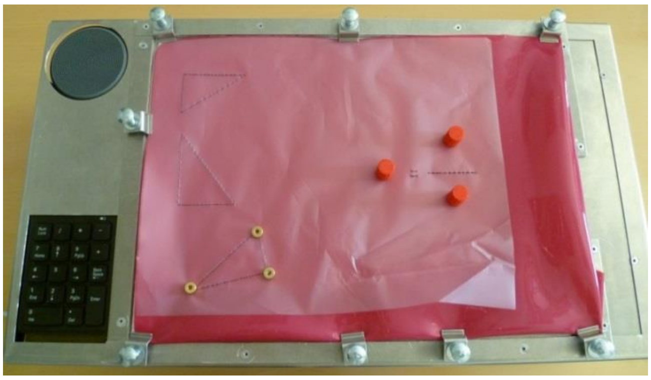

Figure 4.7. The trigonometric ratios application. Three tangible objects are used to represent the vertices of the triangle. Three others are used to represent the hypotenuse, opposite and adjacent sides and can be moved from the triangle towards the formula.

At the beginning of each activity, users are asked to place a tangible object on the three vertices of one triangle drawn on the German film. At any time, users can switch from one triangle to another by moving the A, B and C tangible objects to another triangle. The first activity is an exploratory activity: by moving the tangible cursor close to the different sides of the triangle, students can retrieve their names (e.g. "this side is the opposite side of the angle BAC"; "this side is the hypotenuse"). During the second activity, students are asked to place the tangible objects representing the different sides in their correct place. If the tangible objects are misplaced, feedback is provided (e.g. "you confused the opposite side and the adjacent side""). During the third activity, which is illustrated in Figure 4.7, students are also asked to place the tangible objects representing the sides in their correct place. Then, they are asked to compute the sine/cosine/tangent of one angle: they must move the tangible objects "into" the formula and position them in their right place[57]. If they are correctly placed, feedback is given. Finally, by "shaking" the tangible object on the left side of the equation, students can retrieve the corresponding result (e.g. "the sine of BAC is 0.70").

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[56] It is possible to envisage an application or activity that will help students draw right-angled triangles of different sizes and orientations.

[57] The idea of moving the tangible objects from the triangle towards the formula was suggested by the teachers, who thought that this action (and its associated proprioceptive feedback) would help students memorize the formula, and also better understand the link between the geometric shape and the arithmetic formula.

6 DISCUSSION AND PERSPECTIVES

6.1 HARDWARE AND SOFTWARE IMPROVEMENTS AND ADJUSTMENTS

The current version of the Tangible Box offers a number of interesting features. However, in terms of hardware and software, several improvements and adjustments could be considered for future versions to improve its usability. Firstly, teachers who participated in the brainstorming found the Tangible Box bulky, although it is more compact and portable than traditional TUIs. In particular, they expressed concern about the height of the Tangible Box (21 cm). To further reduce its height, it might be possible to use special lens and/or mirrors, in addition to or in lieu of the wide-angle camera that we used. However, such a solution would require more complex computer vision algorithms to correct the image, which may be an issue. Different adjustments could also be made to the lid of the Tangible Box. For example, although the fastening system is easy to use and efficient, it may hinder the user's movements as it relies on eight holding elements located on the surrounding frame. A more compact (and flat) system would be worth considering, such as magnetic clip strips and paper holders[58]. Also, some adjustments regarding the strength of the magnets are needed to reduce the friction, which quickly damages the supports; another alternative would be to use an additional transparent and thin plastic film on top of the supports to protect them.

Concerning the software, the current version of the prototype can detect only six objects. However, using existing tracking algorithms, it will be possible to detect and identify a larger number of objects (is in the ColorTable [184], for example). Also, with such an algorithm, the framerate could be increased and the size of the lower part of the tangible objects reduced.

6.2 DESIGN SPACE OF TASKS FOR TABLETOP TANGIBLE MAPS AND DIAGRAMS

Throughout this chapter, we described and discussed a number of activities and tasks, which were mainly identified based on participatory design sessions conducted with specialized teachers. Although they were initially identified to facilitate the design of applications for the Tangible Box, we believe that they could also be adapted for other tabletop TUIs for visually impaired users. In fact, the four tasks that we identified (exploration/manipulation, annotation/edition, reconstruction and construction) were also supported by some prototypes that we described in Chapter 2, Part E. In addition, it would also be interesting to specifically investigate the benefits of one type of activity (e.g. trial and error) in terms of learning, and, based on empirical findings, to provide more precise guidelines for each of these activities.

Furthermore, a number of TUIs for learning have already been proposed for sighted users, and it might be interesting to draw inspiration from the applications they proposed. For example, the Teaching Table [135] covered a number of topics, such as counting, identifying patterns, sorting similar objects, comparing geometric shapes, etc. In [18], three activities were proposed and were related to geometry: classifying quadrilaterals, discovering the protractor and describing angles.

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[58] See https://hangmanproducts.com/products/the-clip-strip?variant=379181827 for example

6.3 ALLOWING TEACHERS TO DEVELOP THEIR OWNS APPLICATION

The design framework that we proposed serves two main goals: 1) helping teachers design applications taking full advantage of the Tangible Box; 2) facilitating communication between teachers and developers by providing a common frame of reference to describe the applications. However, the design framework can also be used to identify a number of modules that are common to different applications (e.g. TTS and tangible menus). These modules could be implemented so that they could easily be parameterized (e.g. using xml configuration files) and be used as building blocks to create custom applications, foregoing the need to develop them from scratch.

If a sufficient number of modules were developed, it could even be envisaged that teachers would be able to develop applications on their own, using a dedicated GUI and simple (graphical) programming language, similar to the Scratch 4 Arduino[59] (S4A) software. In fact, the feasibility of letting teachers develop their own tangible interfaces has been successfully demonstrated by Maquil et al. [185] and Schwartz et al. [275], who proposed a new tool for the development of tabletop tangible interfaces, called COPSE, and evaluated its use during a workshop organized with 33 teachers. Examples of modules could include:

- A "TTS" module with basic features: start, stop, select voice, select language, select pitch.
- A "tangible menu" module, defined by a list of items, a layout (e.g. pie menu or rectangle menu) and the ID of the tangible object used to interact with the menu.
- A "guidance" module for reconstruction tasks, with different parameters similar to those mentioned in section 4.2.3 (e.g. units for distances, units for directions).
- An "interaction" module that detects whenever the user is interacting with one tangible object, which would specify the mode of interaction (e.g. using a tangible cursor, moving the object, shaking the object, etc.).

6.4 BRING YOUR OWN PHONE

Over the last decade, the use of personal devices to interact with public applications has become more and more frequent and a number of research projects investigated the use of mobile phones to interact with public displays or interactive surfaces. This new paradigm, often referred to as BYOD (for Bring Your Own Device) presents two main advantages: firstly, it does not require buying dedicated hardware, which would increase the cost of the interface; secondly, it enables users to interact with the system with a device they are already familiar with and that they have already configured. This is particularly important for visually impaired users, who need to adjust a number of parameters about audio feedback (voice, pitch, speed, etc.). We foresee three ways in which using smartphones could enhance the Tangible Box.

6.4.1 TRACKING FINGERS AND OBJECTS WITH A SMARTPHONE'S INTEGRATED CAMERA

One downside of the Tangible Box is that it does not support touch-based interaction. Although we described how a tangible object can be used to select other tangible objects or tactile elements in order to retrieve their name, having the possibility to directly interact with these objects and

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[59] http://s4a.cat/

elements by pointing at them would be interesting. Also, the Tangible Box can only recognize the lower part of the tangible objects (i.e. the part below the surface). Therefore, the system cannot be aware if two upper parts have been involuntarily switched by the user. In addition, if instructions are given to the students to put a particular hat on top of one tangible object, the application cannot check whether the hat has been placed on the correct tangible object. For all these reasons, being able to track the users' fingers and the upper parts of the tangible objects may enhance the Tangible Box, although possible hand occlusions will still be an issue. We consider these additional features as a way of complementing existing interaction techniques based on the manipulation of the tangible objects, not replacing them.

Today, a smartphone's integrated camera provides a sufficient resolution to track and identify fingers or objects (e.g. [109,175]). For example, we already described the prototype of Götzelmann [85,89], which enabled visually impaired users to interact with a 3D-printed map by performing pointing gestures that were detected by the user's smartphone's integrated camera. More recently, ManoMotion[60] released a SDK for hand-tracking, compliant with tablets and smartphones cameras, and which notably supports the detection of "a set of predefined gestures, such as point, push, pinch, swipe and grab". Another well-known example is Osmo[61], a set of games for children that use the iPad's camera to track objects and provide feedback accordingly. Therefore, the Tangible Box could be equipped with a system to hold the user's smartphone above the surface and provide additional interaction techniques that may enhance the user's experience. In particular, the smartphone's camera could be used to track tangible menus similar to those proposed by Ullmer et al. [309], which consist in a card on which a number of core features (e.g. save, copy, paste, etc.) are printed, or similar to those proposed by Bonnard et al. [18], which also consist in a set of tangible cards.

6.4.2 SMARTPHONE-BASED MENUS

Another potential use of smartphones is to use them as an input device. Instead of (or in addition to) using the numeric keypad, students could directly interact with their smartphone to launch an application, adjust different parameters (e.g. levels of complexities), input text, record voice messages, etc. In fact, as visually impaired users are already familiar with touch-screen menus, it might be easier for them to interact with their smartphone than with the keypad. In addition, in the framework of the AccessiMap project, a Master's student developed a number of smartphone-based menus that enabled visually impaired users to interact with a tangible map. Although the system has not been evaluated by visually impaired users, results from informal tests with blindfolded participants were encouraging.

6.4.3 SMARTPHONE-BASED USER IDENTIFICATION

As we already discussed when introducing the design framework, enabling the user to log into the application opens interesting perspectives. For example, different feedback could be provided depending on the user's age, level or familiarity with the activity. Also, if one student modifies the digital information (e.g. with personal annotations), it might be interesting to provide him/her with a way to load the same content during the next session. Finally, if the user logs into the

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[60] http://manomotion.com/ (see https://developers.manomotion.com/ for videos and SDK)
[61] https://www.playosmo.com/en/coding/

application, the application can track their performances over time (e.g. number of errors in solving a task), which can notably be useful for teachers. An even more convenient method would be for the Tangible Box to identify the smartphones around the table to automatically log in the users.

7 CONCLUSION OF CHAPTER 4

In this chapter, we described the design and implementation of a tabletop TUI that can give visually impaired students access to a number of learning activities. More precisely, on the basis that there is a shortage of educational TUIs for visually impaired users, we developed the Tangible Box, which fulfills the following criteria: it is a compact and self-contained TUI, meaning that several teachers could each own one device; it is relatively low-cost (less than 300 €); it fulfills the "stability" criteria, which we identified as an important design consideration of tabletop TUIs for visually impaired users, and, very importantly, it can be adapted to a large range of topics, tasks and user profiles. To achieve this last criterion, we proposed to use tangible objects that are composed of two magnetic parts: by placing one part above and the other part below the surface we ensure the stability of the tangible representation, avoid hand occlusions, and we also make it possible to use traditional supports of different thicknesses such as raised-line or swell graphics. In addition, the tangible objects that we designed are very generic and can be adapted to specific activities by 3D-printing a "hat" that can be used to customize the tangible objects. Although this interface is still under development, we began investigated its potential for learning by asking five specialized teachers to imagine applications. Based on their ideas, we also proposed a design framework for the Tangible Box, composed of four main themes (overall characteristics, material, activities and interactivity), and from which we more thoroughly investigated the design space of tasks for tabletop maps and diagrams for visually impaired users. Finally, we proposed a number of perspectives, notably concerning the use of students' smartphones.

CHAPTER 5

BOTMAP: PANNING AND ZOOMING WITH AN ACTUATED TUI

> *Je suis revenu au bureau et j'ai fait face à mes obligations statistiques jusqu'à sept heures mais j'ai eu beaucoup de mal parce que je tendais au zéro à une vitesse vertigineuse.*
>
> Romain Gary (Emile Ajar). Gros-Câlin.

Chapter structure

Related publication

J. Ducasse, M. Macé, B. Oriola, C. Jouffrais. *BotMap: non-visual panning and zooming with an actuated tabletop tangible interface*. Journal article. Under submission.

1 INTRODUCTION

1.1 MOTIVATIONS

In the two previous chapters, we investigated different tasks and types of graphical representations. In addition, we proposed two technical solutions to enhance the tangible representation: with the Tangible Reels, we proposed the design of innovative tangible objects that can be used to make digital lines tangible; with the Tangible Box, we proposed to augment traditional supports such as raised-line graphics with tangible objects. However, the degree of updatability of these two interfaces is constrained by the fact that users must reposition the objects themselves, which takes some time, especially in the absence of vision.

In Chapter 2, Part D, 4, we introduced the concept of actuated tabletop TUIs, which are composed of a set of tangible objects that can move independently, therefore foregoing the need for the user to reposition the tangible objects one after the other. Such interfaces open various perspectives in terms of tasks and graphical representations, notably because they are able to give users access to physical and yet highly reconfigurable representations. Although they require additional hardware and are therefore more expensive than traditional tabletop TUIs, they are a promising area of research. In fact, with the advent of robotics, it is becoming easier to buy or build small, affordable and fast robots. For example, we already mentioned the work of Le Goc et al. [81], who recently developed a platform composed of numerous Zooids, which are small (2.6 cm), affordable (50 $) and high-speed (44 cm/s) custom-made robots. In Chapter 2, Part E, 3.2, we also described the Interactive Auditory Scatter Plot prototype, which was developed to make scatterplots accessible to visually impaired users: tangibles objects moved to the center of data clusters to help users locate them.

In this chapter, we investigate how actuated tabletop TUIs can be used to make maps composed of a large number of *points* accessible to visually impaired users. These types of map are not particularly adapted for Orientation & Mobility, but they are very useful for exploring geographical spaces of various scales: a world map with the largest cities and/or capitals, a country map with the biggest cities or the main places to visit, a city map with particular points of interest such as shops, subway stations, etc. These maps are also often used to let users explore geostatistical data: for example, each point can represent a city and be associated with a value (unemployment rate, temperature, etc.). However, due to their large number of elements, they often require panning and zooming–two advanced functionalities that have rarely been studied for visually impaired users. In this work we propose an innovative actuated tabletop TUI that supports the display of physical and highly updatable maps, and investigate the design of non-visual interaction techniques for panning and zooming.

1.2 RELATED WORK: PANNING AND ZOOMING INTERFACES

In Chapter 2, Part D, 4, we already provided a review of the literature on actuated tabletop TUIs. In this section, we briefly review the literature on panning and zooming interfaces, focusing on non-visual interaction techniques for panning and zooming. According to Hornbaek et al. [104], "panning changes the area of the information space that is visible, and zooming changes the scale at which the information space is viewed". The visible area of the canvas is often referred to as the *view* and it is displayed inside the *viewport* [124]. For panning, two conceptual models can be used [7]: users can either move the canvas directly (e.g. using “grab/touch and drag” techniques) or move the viewport over the canvas (by using navigational tabs or by moving a field-of-view box displayed within an overview window). Panning operations can be *continuous* (in which case the user can move the canvas or the viewport in any direction), or *constrained/discrete* (in which case the user can move the canvas or the viewport a predefined distance by a predefined set of directions).

For zooming, sighted users can usually select a scale by moving a slider along a vertical or horizontal axis, by pressing zoom-in or zoom-out buttons, or using the mouse wheel [124]. The number of scales that the user can select depends on the implementation and/or the input technique. Two main types of zoom exist [11,104]: geometric (all elements are always displayed, whatever the scale, but the size of the icons depends on the chosen scale) or semantic (different elements are displayed at different scales, for example the name of buildings or rivers only appear beyond a certain scale). When panning (and zooming) at higher scales, users may experience "*desert fog*" if the part of the map displayed does not contain any elements, and users may feel lost or disorientated [127].

For visual panning and zooming, the effect of various factors on users’ performances, satisfaction and spatial abilities have been investigated: presence or absence of overviews, comparison of input techniques, use of animation when zooming, display sizes, etc. In addition, frameworks, toolkits, novel input techniques and navigational aids (e.g. to avoid desert fog) have been proposed (see [11] for examples).

The literature on non-visual panning and zooming is much more sparse. Panning and zooming functionalities have mainly been implemented with raised-pin displays [115,270,350]. Input techniques included buttons [270] or drag-to-pan and pinch-to-zoom gestures [350], but were not evaluated per se. Interestingly, Shimada et al. [280] enhanced a raised-pin display with two tactile scroll-bars (one horizontal and one vertical), each equipped with a motorized knob. The scroll-bars’ lengths represented the height or width of the entire graphic; the knob position within the scrollbar indicated the horizontal or vertical position of the current area displayed with respect to the entire graphic. Even though the knob could not be moved by the users to perform panning operations, evaluations conducted with blindfolded users showed that it helped users locate an element within the entire graphic. With Linespace [292], users could ask the system to extend the map currently displayed (similar to panning) or to 3D-print a detailed view of the area (similar to zooming). With iSonic [352], a tool for the exploration of geostatistical data, a numeric keypad enabled users to zoom in or out using a 3*3 recursive grid, a technique first proposed by Kamel et al [130].

Different algorithms have been proposed for non-visual zooming. Palani et al. [226] proposed two types of zoom for touchscreen devices: with Fixed zoom, the elements displayed at Level 1 are displayed at Level 2 alongside new elements; with Functional zoom, different elements are displayed at different zoom levels (e.g. walls at Level 1 and corridors at Level 2). These two zooming modes were compared to a no-zoom condition. Even though the evaluation was conducted with sighted and blindfolded participants, results showed that users managed to build an accurate cognitive map regardless of the conditions. Rastogi et al. [248] developed an algorithm that determines intuitive zoom levels for the exploration of detailed diagrams, based on a tree hierarchy of the diagram elements.

1.3 RESEARCH QUESTIONS

Despite being very promising, actuated tabletop TUIs have not been used to display physical and dynamic maps which are accessible to visually impaired users. A few prototypes have implemented non-visual panning and zooming functionalities but their usability has not been studied and it is unclear whether they enabled visually impaired users to efficiently navigate and understand the maps. Although the work of Palani et al. [226] addressed similar questions, their study was limited to simple and non-physical maps and was conducted with blindfolded participants only. In this work, we tackle the issue of non-visual panning and zooming by addressing the following questions:

- **How to design usable non-visual interaction techniques for panning and zooming on an actuated tabletop TUI?** To date, non-visual interaction techniques that have been proposed for panning and zooming have not been evaluated, and those that have been proposed where inspired by visual interaction techniques, such as drag and pinch gestures. In absence of visual feedback, these techniques may not be as efficient for visually impaired users as they are for sighted users. In particular, the design of suitable audio feedback is essential to help users know which part of the map is currently displayed.
- **Which panning and zooming models should be used or are preferred by visually impaired users?** Two models exist for panning and zooming: discrete vs continuous. Although allowing users to have full control over the interface by providing them with continuous panning and zooming interaction techniques seems interesting, it may also led to usability issues: users may have difficulty in finding how to move the viewport or the map or to what extent they must zoom in or out in order to recover a part of the map already explored. With discrete panning and zooming, it may be easier to recover the same configuration (scale and viewport's or map's position).
- **To what extent visually impaired users can understand large interactive spaces whose exploration requires panning and zooming?** Not only the proposed interaction techniques must enable users to move the map/the viewport and select a scale efficiently, but they must also enable them to build a correct mental representation of the map that they are exploring. Therefore, assessing users' mental representations is essential to evaluate the usability of the interaction techniques and the relevance of developing panning and zooming maps for visually impaired users.
- **Is comprehension influenced by one particular interaction technique/model?** If different interaction techniques and/or models are used, assessing their impact on users' mental representations is interesting, in particular for the design of future "pan & zoom" maps for visually impaired users.

To address these research questions, we developed and evaluated BotMap, an actuated tabletop TUI that allows for the display of physical and dynamic maps, and supports non-visual panning and zooming.

1.4 CHAPTER STRUCTURE

In this chapter, we first present the design and implementation of BotMap (section 2), and particularly of the two interfaces that we developed: the Keyboard interface provides discrete panning and zooming while the Sliders interface provides continuous panning and zooming. In the second section, we describe a first evaluation conducted with blindfolded participants, which aimed at assessing the usability of the two interfaces. In section 3, we report on the evaluation of the two interfaces by visually impaired users, focusing on the impact of panning and zooming on participants' mental representations. In section 4, we introduce four additional features that we developed in order to help users better navigate the map and that we presented to blindfolded and visually impaired participants during participatory design sessions. Finally, in section 5, we review the main findings and limitations of this project and discuss some perspectives for further research on the design of actuated tabletop TUIs for visually impaired users as well as on the design of non-visual "pan & zoom" maps.

2 SYSTEM OVERVIEW AND INTERFACES

The design of BotMap was based on an iterative process, which included several brainstorming sessions and pilot tests with one blind person, one visually impaired person and six blindfolded participants (including three HCI experts and one ergonomist). In this section we describe the main aspects of BotMap, as well as how panning and zooming can be performed using the Keyboard and the Sliders interfaces.

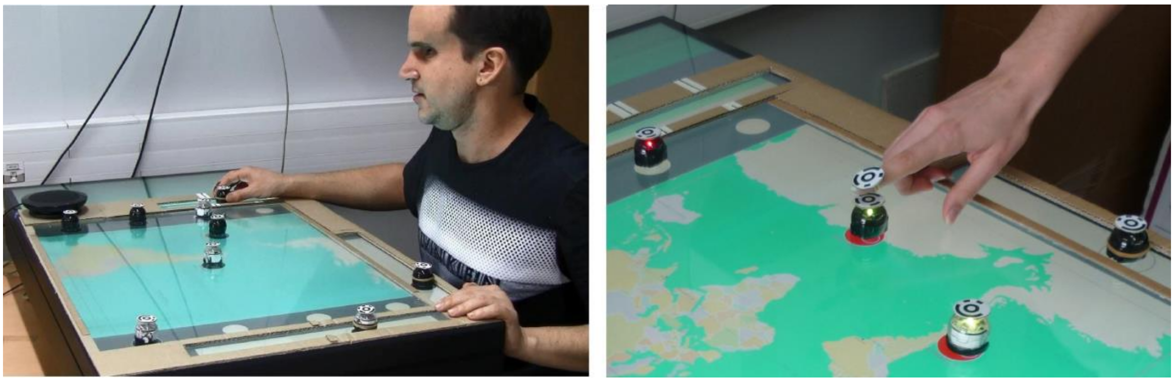


Figure 5.1. Overview of BotMap. Left: BotMap is composed of an interactive tabletop and several robots, tracked by a camera. Each robot represents a landmark and moves to its new position whenever the map is refreshed. In the picture, a blind user is zooming with the Sliders interface. Right: Users can select a robot to retrieve the name of the corresponding landmark.

2.1 SYSTEM OVERVIEW

In BotMap, landmarks are represented by robots that are tracked by a camera placed above an interactive table and that can move freely on the surface whenever the map is updated (Figure 5.1, left). Users can explore the map using both hands and they can interact with the robots in order to retrieve the names of the corresponding landmarks (Figure 5.1, right). They can also ask for other pieces of information using voice commands. When panning and zooming, feedback concerning the viewport position and the scale (i.e. how many kilometers the viewport represents) is provided. When the user confirms the ongoing operation, the robots move to their new position.

Maps are composed of several landmarks. Because all landmarks cannot be displayed at the same time (a limited number of robots can be used simultaneously), semantic zooming must be used instead of geometric zooming. We defined three zoom levels, and each landmark appears at a certain level depending on its type (city, town or village): at the City level, only the cities are displayed and the whole map can be displayed within the viewport; at the Town level, the cities and the towns are displayed; at the Village level, the cities, towns and villages are displayed. Users can switch between these levels by zooming in or out.

2.2 DESIGN RATIONALE

2.2.1 INPUT MODALITIES

The design space of interaction techniques above or around an interactive table is large and mainly includes touch interaction, tangible interaction, mid-air interaction or the use of regular devices such as a keyboard/mouse or voice commands. Throughout our iterative design process, we found that touch-based techniques were not suitable for panning and zooming, as unintentional inputs were often triggered, making it difficult to correctly perform a gesture. Mid-air interaction techniques have been successfully used to enable visually impaired users to interact with a map [6]. However, the detection of gestures is usually performed with a motion-capture system and therefore requires additional and expensive hardware. On the other hand, keyboards and tangible objects are cheap and provide tactile and/or kinesthetic feedback. In particular, keyboards are the most common input devices for visually impaired users to interact with computers. Keyboard and tangible objects have been successfully used in various prototypes developed for visually impaired users, notably to navigate a map (e.g. keyboard in iSonic [352]) or a graph (e.g. tangible slider in the Tangible Graph Builder [196]). Building on these successful prototypes, we used a numeric keyboard for discrete panning and zooming (Keyboard Interface) and tangible sliders for continuous panning and zooming (Sliders interface). Users can also interact with the system using voice commands.

2.2.2 IMPLEMENTATIONS OF PANNING AND ZOOMING

In this section, we briefly explain the decisions concerning the choice of particular implementations for panning and zooming.

Discrete vs continuous panning and zooming. Two models exist for panning and zooming [7]: discrete vs continuous. In order to evaluate whether one model could be more usable than the other, we designed two interfaces: the Keyboard interface allows discrete panning and zooming while the Sliders interface allows continuous panning and zooming.

Clutch-free panning and zooming. During the design process, various techniques were implemented and evaluated. Based on these preliminary tests, we decided not to implement any interaction technique that would require "clutching" operations (when users must lift their finger or the object they are manipulating and reposition it [213]). These operations are cognitively demanding because they disrupt the panning and zooming processes. We therefore discarded “drag-to-pan” and “pinch-to-zoom” interaction techniques, as they might require clutching.

Moving the map vs. moving the viewport. To our knowledge, the question of which panning implementation should be used for visually impaired users has never been addressed. However, visually impaired users do extensively use panning when using a screen reader or a refreshable Braille display. On these devices, pressing "down" results in listening or displaying the line below the current line and is therefore similar to moving down the viewport. According to this observation, during the design process, we decided to implement panning that requires users to move the viewport instead of the map.

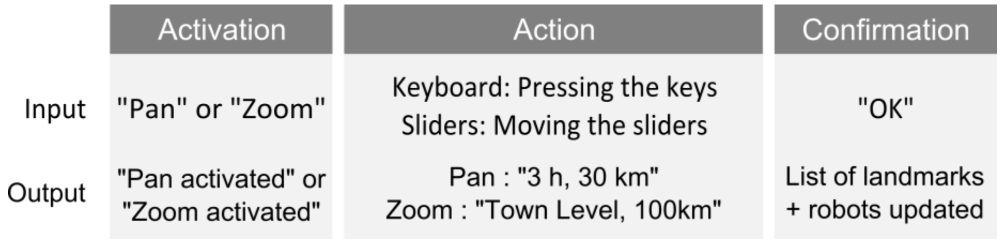
2.3 DESCRIPTION OF THE KEYBOARD AND SLIDER INTERFACES

The voice commands and feedback for panning and zooming are the same for the two interfaces (Figure 5.2). However, the input techniques differ between the two interfaces (Figure 5.3 and Figure 5.4). In this section, we first describe the voice commands and feedback for activation and confirmation, and then describe the input techniques.

2.3.1 ACTIVATION / CONFIRMATION

Users can activate the pan or zoom modes using the voice commands “Pan” and “Zoom”. The message “pan activated” or “zoom activated” is then played. When panning, feedback concerning the viewport’s position is given, with respect to its original position (i.e. at the time of activation). Direction is given using an analogy of the 12-hour clock (3 hours means that the viewport has been moved to the right); distance is given in kilometers. The frequency at which feedback is given depends on the interface and is described in the following sections. When zooming in or out, feedback concerning the zoom level and scale is provided (e.g. “Cities level. The viewport represents 100 km.”).

When the user confirms the current operation (voice command “ok”), the names of the landmarks that have disappeared and appeared are given (e.g. “Previous towns: *Bordeaux*. New city: *London*. New town: *Bristol*.”). At the same time, the robots move to their new position. When the robots are correctly positioned, the message “ok” is played. Users may also cancel the ongoing operation.



	Activation	Action	Confirmation
Input	"Pan" or "Zoom"	Keyboard: Pressing the keys Sliders: Moving the sliders	"OK"
Output	"Pan activated" or "Zoom activated"	Pan : "3 h, 30 km" Zoom : "Town Level, 100km"	List of landmarks + robots updated

Figure 5.2. Before panning and zooming, users must activate the corresponding mode. They must confirm (or cancel) the action. Audio feedback is the same for the two interfaces.

2.3.2 KEYBOARD INTERFACE

For this interface, the viewport is divided into a grid of 3 x 3 square cells (Figure 5.3, right). A numeric keyboard is placed on the right side of the viewport (Figure 5.3, left). Tactile cues were added to the keyboard to help users find the central key.

For panning, users must press one of the eight direction arrows in order to move the viewport one cell in the corresponding direction. Whenever a key is pressed, feedback concerning the distance and direction of the viewport is provided (e.g. “3 hours, 30 kilometers.”).

For zooming, users have to press the “plus” or “minus” keys. The “plus” key allows users to zoom in: the part of the map displayed in the central cell expands to fill in the entire viewport. The “minus” key allows users to zoom out: the part of the map displayed within the entire viewport shrinks to fill only the central cell. Whenever the “plus” or “minus” key is pressed feedback concerning the current zoom level is provided. The predefined scales are 300 km (zoom level: City), 100 km (zoom level: Town) and 30 km (zoom level: Village). If the user cannot move the viewport (because one of the edges of the map has been reached) or cannot zoom in or out, feedback is provided accordingly (e.g. “Impossible to go to the right”, “Impossible to zoom in”).

The Keyboard interface only provides the *relative* position of the viewport with respect to its initial position[62]. Users cannot infer the position of the viewport on the map.

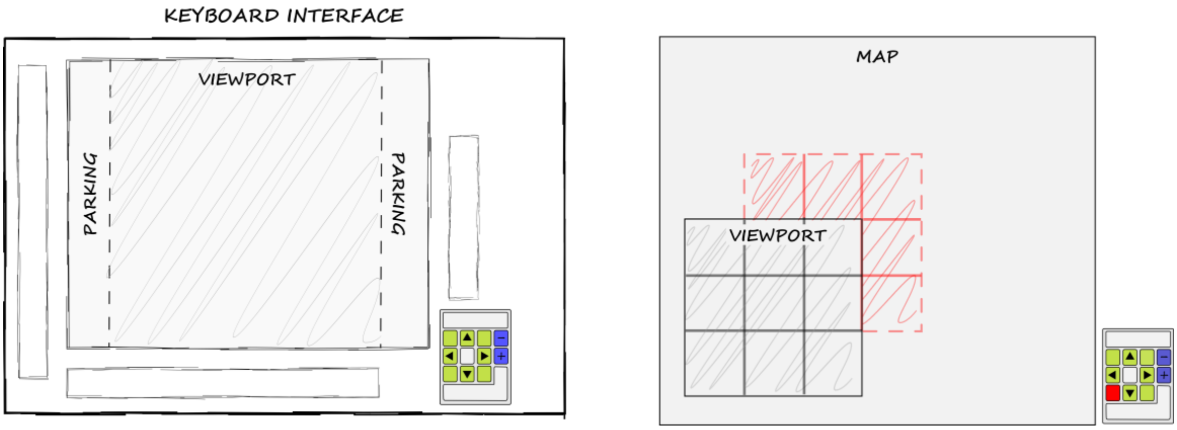


Figure 5.3. Description of the Keyboard interface. Left: for panning, users can move the viewport in any of eight directions by pressing the corresponding key (in green). For zooming, they must press the “plus” (zoom-in) or “minus” (zoom-out) key (in blue). Only three predefined scales can be selected (one per zoom level). Unused robots move to the parking areas. Right: illustration of the viewport with its nine virtual cells, as well as two successive viewport’s positions over the map.

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[62] Feedback concerning the viewport’s position is always given with respect to its initial position. For example, if the user activates the pan mode and then presses the right key, the message “3 hours, 30 km” is played; if the user then presses the right key another time, the message “3 hours, 60 km” is played (the distance between the viewport’s actual position and the viewport’s initial position increases); if the user then presses the left key, the message “3 hours, 30 km” is played (the distance decreases).

2.3.3 Sliders interface

For this interface, three additional robots (referred to as sliders) can be moved by the user inside three rectangular areas delimited by cardboard (Figure 5.4, left). Two tactile cues (rubber-bands) were added on each slider to identify them. The vertical and horizontal areas, respectively to the left of and below the viewport, are used for panning. Users can move the viewport by moving the sliders. The position of the sliders within these areas corresponds to the vertical/horizontal position of the viewport's center over the map (Figure 5.4, right). When panning, feedback concerning the position of the viewport is provided every 2 seconds.

For zooming, a vertical slider area is placed to the right of the viewport. The position of the slider placed within this area represents the current scale of the map, in kilometers. The highest position of the slider corresponds to a viewport representing 300 x 300 km, whilst the lowest position corresponds to a viewport of 30 x 30 km. Any scale between 30 and 300 km can be selected. Feedback concerning the current zoom level and scale is provided every second or as soon as a new zoom level is selected. Tactile cues were placed on both sides of this slider area to indicate the limit between the three zoom levels (City level: between 300 and 150 km; Town level: between 150 km and 80 km; Village level: between 80 km and 30 km).

By touching the Sliders, users can easily retrieve the position of the viewport on the map (see Figure 5.4, left), as well as the current zoom level (City zoom level in Figure 5.4, left) and the approximate scale (around 250 km in Figure 5.4, left)[63].

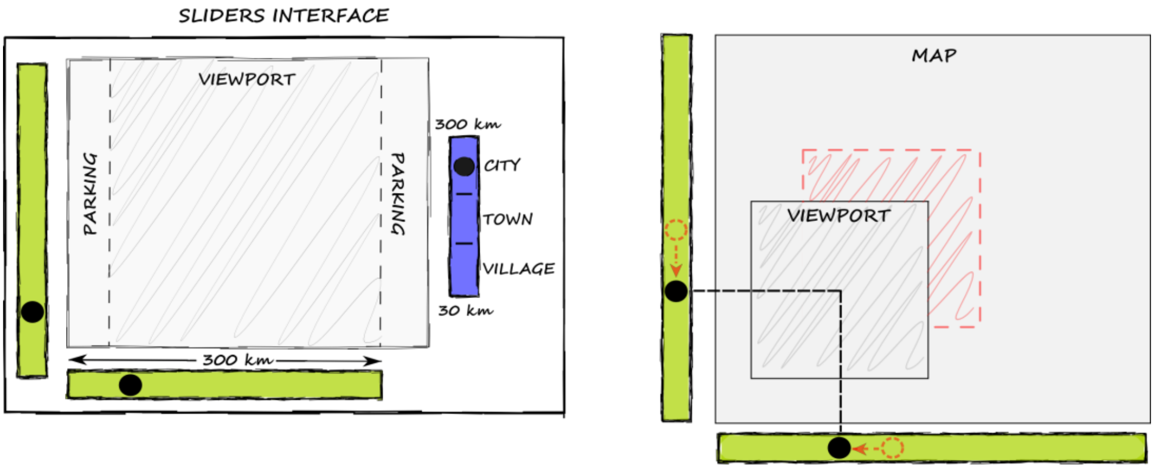

Figure 5.4. Description of the Sliders interface. Left: for panning, users can move the viewport horizontally and vertically by moving two robots (black dots on the green areas) that represent the position of the viewport's center. Users can move the third robot in the zooming area (blue area) to select any scale between 30 km and 300 km. Right: illustration of two successive sliders' and the viewport's positions over the map.

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[63] As with the Keyboard, feedback concerning the viewport's position is always given with respect to its initial position. If the user activates the pan mode and then moves the slider in the horizontal area towards the right, the messages "3 hours, 30 km", "3 hours, 60 km", etc. are played (the distance between the viewport's actual position and the viewport's initial position increases). If the user then moves the slider towards its initial position, the messages "3 hours, 50 km", "3 hours, 30 km" are played (the distance decreases).

2.4 ADDITIONAL COMMANDS

2.4.1 IDENTIFICATION OF LANDMARKS

Users can retrieve the names of the landmarks (Figure 5.1, right). A marker is attached to the index finger and is tracked by the camera placed above the tabletop. To retrieve the name of a landmark, users must place the index on top of the robot. The name is given via Text-To-Speech (TTS), followed by the type of the landmark (town, city or village). When there are more robots than landmarks to be displayed, robots move to parking areas located on each side of the viewport. If the user selects a robot that is on a parking space, the message "parking" is played.

2.4.2 VOICE COMMANDS DURING EXPLORATION

Three voice commands allow users to retrieve additional pieces of information:

- **"List"**. The system lists all the landmarks currently displayed, according to their type (e.g. "Cities: London. Towns: Cambridge"). The message "no landmarks" is given when there are no landmarks displayed.
- **"Scale"**. The system indicates the zoom level as well as how many kilometers the length of the viewport represents (e.g. "Town level. The window represents 100 km").
- **"Repeat"**. The system replays the last message.

2.4.3 CENTERING ON A LANDMARK FOR ZOOMING IN AND OUT

To display more details around a landmark it is necessary to place this landmark at the center of the viewport before zooming in, otherwise it may move out of the viewport when zooming in. We therefore implemented a "centering" functionality that enables users to place any landmark currently displayed at the center of the viewport. Users first need to select the landmark and then use the voice command "Center". The viewport is then repositioned accordingly.

In addition, during pilot tests we observed that when zooming out, participants were sometimes disorientated because a landmark that was displayed at Village level could not be displayed at Town level. This was particularly an issue when users were asked to find the nearest town to a village: when zooming out, the village would disappear. In order to enable users to have a fixed reference between different zoom levels, we modified the zooming algorithm. When the user centers the viewport on a landmark before zooming out, this landmark is displayed at inferior zoom levels until the user centers the viewport on another landmark.

3 IMPLEMENTATION

3.1 HARDWARE

The table is a Multitaction interactive table (MT420S, MultiTouch Ltd, Helsinki, Finland), running Windows 7. The display area is 93 * 52 cm for a diagonal of 42". The different sliders areas are surrounded by thick cardboard (0.5 cm) and border the viewport (see Figure 5.1, left). Two laminated strips are placed at the top and bottom of the viewport to help users distinguish between the viewport and the parking spaces.

Although the table can track fiducial markers, these markers are too large for our application (4 x 4 cm). We therefore used an additional webcam placed above the tabletop to track the robots upon which we attached a small circular marker (2.5 cm diameter). The user's index finger is identified with a marker and tracked by the same camera. A USB speaker and a numeric keyboard (for the Keyboard interface only) are connected to the table.

For the robots, Ozobots Bits[64] (Ozobot & Evollve, Inc.) are used, which are small and light toy robots (2.5 cm diameter x 2.5 cm high, 9 grams). The robots have two wheels and can move at speeds up to 44 mm/s. Ozobots Bits are equipped with a color sensor, and their behavior can be programmed in advance, using the OzoBlockly Editor[65] that is based on the Blockly graphical programming language. Possible behaviors include following a colored line, rotating and changing the LED color. The autonomy of the Ozobots Bits is around one hour when moving. Three additional Ozobots Bits are used as sliders for the Sliders interface, so that the sliders can be repositioned in case the users cancel a panning or zooming operation.

3.2 SOFTWARE

Audio instructions are provided with a SAPI4 compliant TTS engine distributed as part of the CloudGarden TalkingJava SDK 1.7.0. To avoid any issue with voice recognition, vocal commands are triggered by the evaluator using a keyboard.

The BotMap application was developed using the MultiTouch4Java library (MT4J, [156]). Besides receiving TUIO messages sent by the interactive table, the library provides basic methods for panning and zooming. However, the library requires the use of tiled web maps. To work offline, we generated offline map tiles using TileMill[66], an open-source map design studio. The application also manages the robots.

Robots' markers are tracked using the TopCode library, which provides their position and orientation. To improve the precision of the detection, the markers' coordinates are refined using a homography. Whenever the map is rescaled or the viewport repositioned, each robot is assigned a landmark or a parking space, depending on the number of landmarks to be displayed. An algorithm controls the robots in order to avoid collision and lock-up by displaying lines and circles of different colors that make the robots move, pause or rotate. A detailed description of the algorithm used to manage the robots is provided in Appendix C.

4 STUDY 1: USABILITY OF THE TWO INTERFACES

4.1 AIM AND TASK CHOICE

The aim of this study was to evaluate whether the two interfaces enabled users to perform panning and zooming operations of various complexities (panning various distances and directions, with or without zooming). We also aimed to investigate whether one interface was more usable than the other. To do so, we used a basic target reaching task that did not require high cognitive processes but rather basic interaction processes (pressing the keys or moving the

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[64] http://ozobot.com/products/ozobot-bit

[65] http://ozoblockly.com/editor

[66] https://tilemill-project.github.io/tilemill/

sliders). As the aim of this study was to assess usability and not mental representations, we did not expect any significant differences between blindfolded and visually impaired participants.

4.2 MATERIAL AND METHODS

4.2.1 PARTICIPANTS

We recruited 10 sighted participants (2 female, 8 male) from the research laboratory. Participants were aged between 24 and 29 (*M* = 26.4, *SD* = 1.6) and were all right-handed.

4.2.2 MATERIAL

We used the set-up described in the previous section with six robots (in addition to the three sliders in the Sliders Interface). In order to reduce the length of the experiment, the robots were manually repositioned by the evaluator after each user command. Two randomly generated maps were used: 8 landmarks were selected in the first map for the training, and 24 landmarks were selected in the second map for the test. Landmark names were extracted from a list of existing village names and were randomly assigned at the beginning of each trial.

4.2.3 TASK

The task was to find and select a landmark called "Target" as quickly as possible. At the beginning of each trial, a message was played indicating the current zoom level, the zoom level at which the target was present and its direction and distance with respect to the center of the viewport (e.g. "City level. Target city located at 3 hours and 150 kilometers"). At any time (i.e. even when panning), users could ask the system to give the updated direction and distance with the voice command "Info". Distance and direction were given with respect to the current position of the viewport.

4.2.4 EXPERIMENTAL DESIGN AND CONDITIONS

The experiment used a within-subject design with four independent variables and two factors for each independent variable. Therefore, there were 2 * 2 * 2 * 2 = 16 conditions, i.e. 8 for each interface:

- **Interface**. The Keyboard and the Sliders interfaces were compared.
- **Direction**. Targets were either located next to the vertical or horizontal axes (*Vertical/Horizontal*), i.e. North, South, West, East, or next to the diagonal axes (*Diagonal*), i.e. NE, NW, SE, SW. We ensured that all targets were within an angle of 15° around the axis.
- **Distance**. Targets were either located within 40-50 kilometers from the initial viewport's position (*Small*) or within 120-130 kilometers from the initial viewport's position (*Large*).
- **Zoom level**. At the beginning of the trial, the zoom level of the map was either City or Village but all the targets were located at the Village level. Therefore, the initial zoom level and the target zoom level were either identical (*Identical*) or different (*Different*), in which case users had to zoom in in order to display the target.

4.2.5 VARIABLES

To assess the usability of the interfaces, we measured the time required to display and select the target. For each trial, we also logged the successive positions of the viewport and scales. Finally, participants had to fill out the SUS [25] and NASA-RTLX [94] questionnaires[67], and to indicate which interface was the more efficient, which one was the more pleasant, and which one they would choose if they had only one choice, and for what reasons. All sessions were video recorded.

4.2.6 DATA ANALYSIS

To compute point estimates and 95% confidence intervals, we used the same methodology as presented in the user study conducted with the Tangible Reels. For completion times, we computed geometric means and 95% exact CIs on log-transformed data, and pairwise comparisons of completions times are expressed as ratios ([138], [266]). For the other variables, we computed means and 95% bootstrap CIs and, for pairwise comparisons, we computed differences between interfaces for each factor and each participant. However, for distances only we computed ratios between interfaces, instead of differences between interfaces: as the distance that users had to pan depended on the trials (*Small* vs *Large*), computing mean distance differences across different trials would not have been relevant.

4.2.7 PROCEDURE

The experiment was composed of two sessions (one per interface), conducted on separate days but during the same week. Interface order was counterbalanced. Each session lasted approximatively 1h30. The procedure is described in the following table (Table 5.1):

Table 5.1. Procedure for each session of Study 1. There was one session for each interface.

Procedure – Study 1	
Introduction	Explanations concerning the experiment's goal and organization. Consent form + photo/video authorization form.
Basic features	Selection, voice commands (*List*, *Scale* and *Repeat*), centering.
Panning	Explanations using a tactile map and frame + 4 training trials with BotMap.
Zooming	Explanations using a tactile map and frame + 4 training trials with BotMap.
Test	Three trials per condition (24 trials). The same set of 24 trials was used for both sessions and for all participants, but trials were presented in a random order and names changed.
Questionnaires	SUS and ranking questionnaires.

4.3 RESULTS

4.3.1 COMPLETION TIMES

Because different strategies were used to select the landmark once it was displayed (such as asking for the system to provide distance and direction with respect to the viewport's center), we only report times required to display the target. All participants managed to display and select the

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[67] See Chapter 3, 6.1.2 for an explanation concerning the choice of the questionnaires.

target within the allowed time (3 minutes). Times were similar between the two interfaces (Keyboard: *mean completion time* = 25.8 s, 95% CI [19.8, 33.5]; Sliders: *mean completion time* = 26.8 s, 95% CI [23.3, 30.7]). However, with the Sliders, participants took consistently longer to perform *Diagonal* than *Vertical/Horizontal* trials (orange bars in the central row of Figure 5.5, left).

Figure 5.5 (right) shows pairwise comparisons between the two interfaces, expressed as ratios. Values superior to 1 indicate that participants took longer with the Sliders than with the Keyboard. Overall, participants took as much time to perform the tasks with the Keyboard as with the Sliders, although they tended to take longer with the Sliders than with the Keyboard for *Small* and *Diagonal* trials. The mean ratio between completion times, computed across all conditions, was 1.0, 95% CI [0.8, 1.2].

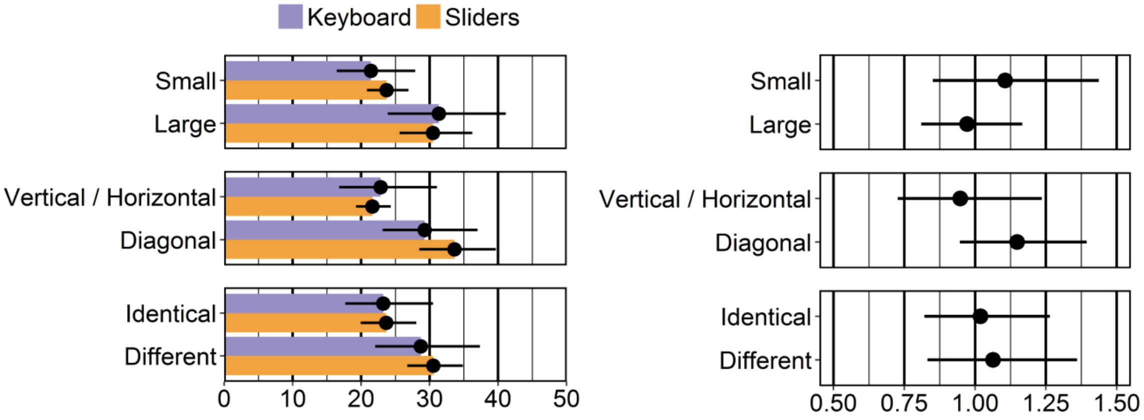

Figure 5.5. Left: Mean completion times per condition, in seconds (N = 8). Right: Mean ratios of completion times (Sliders / Keyboard, N = 8). Values superior to 1 indicate larger times for the Sliders than for the Keyboard. Error bars show 95% CIs.

4.3.2 DISTANCES PANNED

We computed the distance panned by the participants to reach the target in each condition (in kilometers). Results show that participants panned larger distances for *Diagonal* than for *Vertical/Horizontal* trials with the Sliders (orange bars in the central row of Figure 5.6, left). With the Keyboard, participants tended to pan smaller distance when the zoom level was *Identical* than when it was *Different* (purple bars in the lower row of Figure 5.6, left). This suggests that when the zoom level was *Different*, participants performed unnecessary panning actions at the City level.

Figure 5.6 (right) shows pairwise comparisons (Sliders / Keyboard). Values superior to 1 indicate that participants panned larger distances with the Sliders. Given the fact that interval endpoints are about seven times less plausible than the point estimate [44], participants tended to pan larger distances with the Sliders, and in particular for trials where the distance was *Small* (*ratio* = 1.4, 95% CI [1.2, 1.8]), the direction *Diagonal* (*ratio* = 1.3, 95% CI [1.1, 1.5]) and the zoom level *Identical* (*ratio* = 1.3, 95% CI [1.2, 1.5]). This was confirmed by the mean ratio of distances panned, computed across all conditions, which was 1.3, 95% CI [1.2, 1.6].

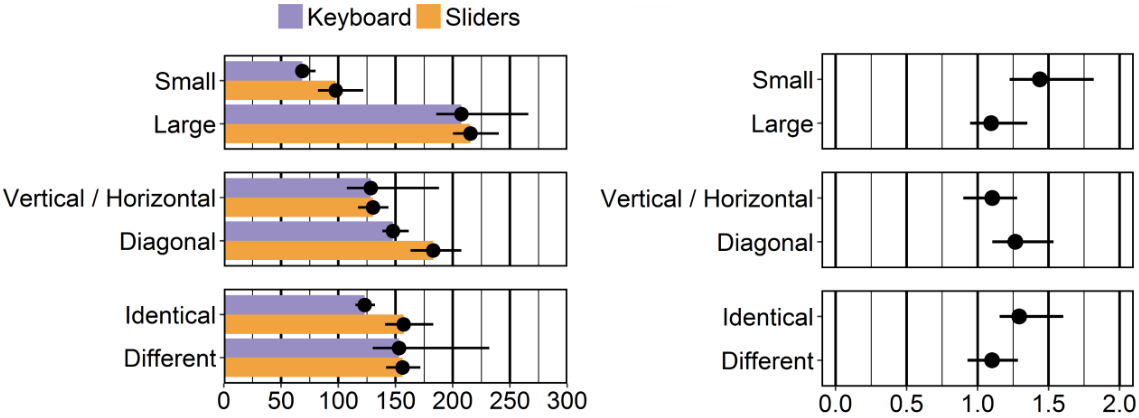

Figure 5.6. Left: mean distance panned (in kilometers) per condition (N = 8). Right: mean ratio of distances panned (Sliders / Keyboard, N = 8). Values superior to 1 indicate that participants panned larger distances with the Sliders than with the Keyboard. Error bars show 95% bootstrap CIs.

4.3.3 NAVIGATION STRATEGIES

As a reminder, users could select any scale between 30 and 300 km with the Sliders (City level: between 300 km and 150 km; Town level: between 150 km and 80 km; Village level: between 80 km and 30 km). With the Keyboard, there was only one predefined scale per zoom level (City level: 300 km; Town level: 100 km; Village level: 30 km).

With the Sliders, two participants (P5, P10) systematically selected the largest scale of the Village level (80 km) in order to maximize the displayed area, regardless of the initial zoom level. Other participants very rarely changed the scale when the initial zoom level was Village. When the initial zoom level was City, two participants (P7, P8) systematically selected the smallest scale of the Village level (30 km) and therefore minimized the displayed area; others (P1, P2, P3, P4, P6 and P9) tended to systematically select the largest scale of the Village level (80 km).

With the Keyboard, when the initial zoom level was City level, four participants (P1, P3, P5 and P7) almost systematically zoomed in to the Village level before panning, regardless of the distance to the target. In contrast, other participants tended to perform panning operations at the City and Town Levels when the distance was *Large*, regardless of the initial zoom level, in order to pan larger distances with a single action.

We also observed that the final position of the target within the viewport varied between the two interfaces: with the Sliders, 45.8% of the targets were located in the center of the viewport at the end of the trials, vs. 26.2% for the Keyboard

4.3.4 SATISFACTION AND FEEDBACK

The overall score for the SUS questionnaire (out of 100) was 85.5 for the Keyboard (95% CI [77.0, 91.2] and 86.0 for the Sliders (95% CI [80.7, 90.7]). Four participants out of ten found the Keyboard interface more efficient than the Sliders, and five found it more enjoyable than the Sliders. Overall, four participants preferred the Keyboard and six the Sliders.

Concerning the Sliders interface, three participants appreciated the fact that they could pan large distances without having to zoom out (P2, P7, P9) and several participants mentioned the usefulness of the tactile cues in the zooming areas (P5, P6, P8). Participants preferred the Sliders because they were easier to use (P6, P10), more precise (P7) and intuitive (P8), but also because they could be used to move the viewport in any direction (P2, P6) and that, compared to the Keyboard, they were based on large movements with both hands (P8, P9). However, several participants reported that practice and time were necessary in order to learn how to use both sliders simultaneously (P5) or to correctly position the sliders (P5, P9, and P6).

Concerning the Keyboard interface, half of the participants found that it was sometimes difficult to distinguish between the directional keys (for panning) and the plus and minus keys (for zooming) and suggested that the two sets of keys should be more clearly separated. They also reported that the Keyboard interface enabled them to move the viewport to a certain distance by "counting" the number of key presses. This feature was the main reason why the Keyboard was found more efficient than the Sliders (P1, P3, P4, P5) or less efficient (P10) and less enjoyable (P6, P7).

4.4 DISCUSSION AND SUMMARY OF STUDY 1

The results show that all participants managed to successfully perform the task with the two interfaces, each in less than 30 seconds. Completion times indicate that overall, participants took as much time with the Keyboard as with the Sliders interface. However, participants tended to pan larger distances with the Sliders than with the Keyboard, especially for *Small*, *Diagonal* and *Identical* trials. This is in line with the fact that, with the Sliders, participants took longer and panned larger distances to perform *Diagonal* than *Vertical/Horizontal* trials, whereas this difference was not as clear with the Keyboard. These observations suggest that the Sliders are less easy to control than the Keyboard when the viewport must be moved diagonally or for small distances. As suggested by some participants, additional practice with the Sliders may have been beneficial in terms of performance.

There were no clear preferences in subjective ranking for one interface or the other. The fact that the Keyboard interface allowed for *discrete* panning was seen by some as an advantage (users counted how many times they had to press each key to reach the target) and by others as a disadvantage (it was not always possible to place the target at the center of the viewport). It is interesting to note that using BotMap, participants managed to develop strategies similar to those that they might have developed using a visual interface, such as zooming out to pan larger distances.

To sum up, this first study showed that the designed input techniques and feedback allowed users to perform panning and zooming actions of various complexities without vision. Both interfaces led to similar performances, with the keyboard having a slight advantage over the Sliders in terms of efficiency (smaller distances panned). In the following study, we specifically investigated whether visually impaired users were also able to efficiently navigate maps through panning and zooming and, above all, to understand them.

5 STUDY 2: USABILITY AND MENTAL REPRESENTATIONS

5.1 AIM AND STUDY DESIGN RATIONALE

The main aim of this study was to evaluate whether our system enables visually impaired users to understand a map whose exploration requires panning and zooming operations. We also wanted to investigate whether one interface would be more usable in terms of efficiency (time to complete a set of actions and comprehension score) and satisfaction.

5.1.1 TASK CHOICE

A few studies investigated the effect of interaction technique on sighted users' navigation and spatial memory performances (e.g. [124,244]). In these studies, the participants first had to navigate a canvas to find particular items (*navigation task*); then, they were asked to relocate the items on the canvas (*spatial memory task*). Navigation performance was assessed by computing "the length of the executed navigation path"; spatial memory performance was assessed by calculating the distance between the correct and estimated x-y coordinates of the items. Besides providing two distinct measures, such a task has the advantage of mimicking a realistic scenario where users would first discover and learn spatial relations between items before recalling these relations to efficiently learn the position of the items. We used a similar task, which consisted in finding specific landmarks before answering questions concerning the landmarks. In addition, in order to ensure that participants would use both panning and zooming, the order of the landmarks to be found was controlled and panning or zooming were either not allowed or mandatory, depending on the trials being performed.

The main difference is that in the above-mentioned studies users were asked to find targets eight times each. This allowed them to reinforce the spatial encoding of the landmarks in spatial memory. However, because tactile exploration is sequential, it takes much longer than visual exploration. In order to keep the length of the experiment within 2.5 hours, two landmarks were explored once and six were explored twice. In order to compensate for the lack of repetition, we assessed mental representations immediately after each trial and did not use distractors.

5.1.2 ASSESSING MENTAL REPRESENTATIONS

In the previously described studies, participants were asked to navigate the canvas using a keyboard to reposition the items. However, such a task can discriminate users whose global mental picture is correct but who are not at ease with navigating the canvas using a keyboard. Other methods have been used or suggested for visually impaired users, which we described in Chapter 2, Part A, 3.3.1. They usually rely on a set of questions or on graphical methods such as sketching, filling blank elements on a map or reconstructing a model using building blocks and cover one or two dimensional aspects of spatial knowledge. In this work, we decided to use both distance and direction questions, as well as a reconstruction task. For the reconstruction, two cities were already positioned to provide anchor points and scale; therefore, similarly to [124], participants had to recall the locations of eight landmarks. The reconstructed maps were compared to the initial map using a bidimensional regression analysis based on Euclidean geometry. This statistical method, initially proposed by Tobler [301], can be used to compute how similar two 2D-configurations are.

5.2 MATERIAL AND METHODS

5.2.1 PARTICIPANTS

We recruited eight legally blind people (five male, three female), aged between 26 and 66 years old (*M* = 46.4, *SD* = 15.0). P2, P3 and P8 had residual perception of very bright light but could not rely on it to distinguish shapes. All participants possess a smartphone and a laptop, and use them very frequently. All participants also reported that, when at school, they had used maps, but at various frequencies. The following table sums up participants' main characteristics (Table 5.2).

Table 5.2. Participants' main characteristics.

	Gender	Age	Age at onset of blindness	Current activity	Usage of maps during school	Self-reported spatial ability
1	Male	66	5	Retired	Occasionally	Excellent
2	Female	44	0	Unemployed	Very often	Average
3	Female	63	0	Civil servant	Occasionally	Excellent
4	Male	44	0	Software developer	Occasionally	Excellent
5	Male	35	4	Unemployed	Very rarely	Excellent
6	Male	60	6 months	Retired	Occasionally	Excellent
7	Female	33	12	Teacher	Occasionally	Average
8	Male	26	16	Unemployed	Very often	Excellent

We asked participants whether they knew how online maps (e.g. Google maps) work, as well as whether they were familiar with the concepts of panning and zooming. Apart from P8 who lost sight at 16, participants knew very little about Google Maps. They mainly knew that Google Maps enables users to compute an itinerary between two points of interest and that this itinerary can be displayed on the map. Other reported some knowledge about Google Street View. For example P5 indicated that "one can enlarge the images to have more details and we can even see streets and cars". As for the concept of zooming, most participants said that it was used to enlarge a picture. None were familiar with the word "panning".

5.2.2 MATERIAL

We used the same apparatus as for Study 1. Four different maps were used for the Training session and the Evaluation session. During training, names of landmarks were either names of planets, musical instruments or vegetables. In that way we ensured that the maps used for training did not interfere with those used for the test. For the evaluation, two maps were used; the second map was symmetric to the first one. Both maps were composed of ten landmarks: three cities, five towns and two villages (see Figure 5.7 for an example). In order to help the users memorize the three cities and their configuration, we used the names of well-known cities and respected their relative locations (for example in Map 2 the western city was labelled Madrid and the eastern was labelled Zurich). The names of the towns and villages were randomly chosen from a list of municipalities so that each landmark began with a different letter. Different names were used for the two maps (see Appendix C).

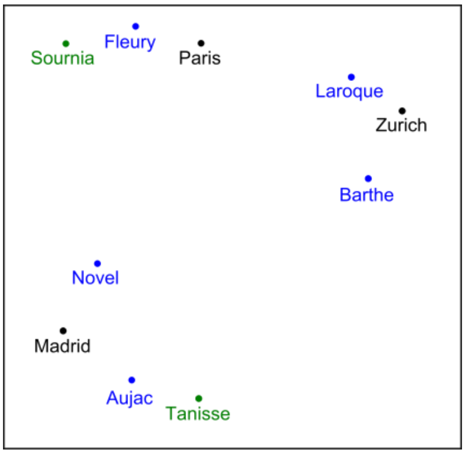

Figure 5.7. One of the two maps used for the test. The three Cities are written in black, the five towns in blue and the two villages in green.

5.2.3 TASK

At the very beginning of the test, users were asked to explore the map at the City level and to memorize the position and names of the three cities. Then, the task was composed of eight trials. In each trial, users had to find one or two landmarks/targets as quickly as possible and were asked to understand and memorize their locations. In order to ensure that participants would use both panning and zooming, the order of the landmarks to be found was controlled and panning or zooming were either not allowed or mandatory, depending on the trials being performed.

To help the subjects locate a target, they were told its type (Town or Village) as well as its approximate position with respect to a reference landmark (given as "R" in the upcoming text), which was a Town or a City already explored. Users had to pan and/or zoom to find the target(s). When they found and selected a target, its name was given, followed by its type and the message "found". At the end of each trial, users were given thirty additional seconds to explore the current view (without panning, zooming or centering). Then, they had to answer four comprehension questions. At the beginning of the following trial, the viewport was repositioned so that all users started a given trial with the same configuration. Figure 5.8 summarizes how each trial was conducted.

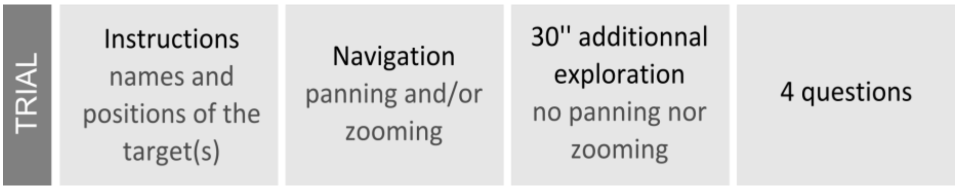

Figure 5.8. Summary of a trial.

5.2.4 EXPERIMENTAL DESIGN AND CONDITIONS

The experiment relied on a within-subject design with two independent variables: Interface (Keyboard, Sliders) and Actions needed in each trial (*Zoom in*; *Pan*; *Zoom in* & *Pan*; *Zoom out* & *in*), i.e. 2 * 4 = 8 conditions. Participants performed two trials for each condition. The trials were presented in the same order for each participant. In that way, participants were "guided" to progressively explore the whole map. For each trial, users had to perform a different set of actions:

- **Zoom in**. The initial zoom level was City level. Users had to zoom in to find two towns located within 60 km of the reference city R. It was possible to simultaneously display the city R and the targets if the viewport was centered on R at the City level.
- **Pan**. The initial zoom level was Town level. Users had to pan in order to find one town located beyond 160 km from the reference town R, within a range of 3 hours (e.g. 6 h – 9 h).
- **Zoom in & Pan**. The initial zoom level was Town level. Users had to find one village located within 60 km of town R, on its left or right side. Users had to zoom in (in order to display villages) and then pan (the target and R could not be displayed simultaneously).
- **Zoom out & in**. The initial zoom level was Town level. Users had to find two towns located within 60 km of city R. Therefore, users had to zoom out, pan to find R, and finally zoom in to find the two targets.

5.2.5 VARIABLES

MAP COMPREHENSION

Two main variables were used: 1) the number of correct answers given by users to the questions asked at the end of each trial; 2) the bidimensional regression coefficient, which indicates how similar two 2D configurations are [301]. Additional questions concerning subjective map comprehension were also asked (see Questionnaire 2 in Appendix C).

Multiple choice questions

Four questions were asked after each trial. They were multiple choice questions with four options. Half of the questions, referred to as *Local* questions, required users to compare landmarks that belonged to the same cluster (i.e. a city and its surrounding towns and villages). The other half, referred to as *Global* questions, required users to compare one landmark to landmarks that did not belong to the same cluster (e.g. City A with towns B1 and B2). Questions concerned either *distances* or *directions*, and required the users to compare two landmarks only (*simple)* or three or more landmarks (*complex)*. In total, 32 questions were asked: 16 were *Local* questions and 16 were *Global* questions; out of the 16 *Local*/*Global* questions, there were four questions of each type (*distance*/*direction* * *simple*/*complex*). The following table gives an example of questions asked after each trial (Table 5.3), and the full set of questions is provided in Appendix C.

Table 5.3. Examples of multiple choice questions asked after each trial. Only one answer is correct.

Question	Type	Answer A	Answer B	Answer C	Answer D
I am in A, facing North. Where is B?	Simple / Direction	12 h – 3 h	3 h – 6 h	6 h – 9 h	9 h – 12 h
	Simple / Distance	< 80 km	80 - 180	180 - 280	> 280 km
Which landmarks are located east of A?	Complex / Direction	B	B, C	C, D	B, C, D
What is the shortest distance?	Complex / Distance	A - B	A - B1	A - C	A - C1

Map reconstruction
At the end of the eight trials, participants were asked to reconstruct the map. To do so, a set of magnets were placed on a magnetic board, each magnet being labeled with the Braille initial of a landmark. Two cities were already placed to provide anchor points and scale, and the edges of the map were delimited with magnetic strips. Participants were read the names of the landmarks before reconstruction. At the end of the reconstruction, a photo was taken and later analyzed to retrieve the coordinates of each landmark.

USABILITY

To assess the usability of the interfaces for visually impaired users, we used the same dependent variables as for Study 1. In addition, because we expected the task to be cognitively demanding, participants had to answer the NASA-RTLX questionnaire [94] at the end of each session[68]. Additionally, several questions were asked concerning the usability of each interaction technique (see Questionnaire 3 in Appendix C). Users also had to indicate which interface they preferred and for what reasons (see Questionnaire 4 in Appendix C).

5.2.6 DATA ANALYSIS

We used the same methods as described in the first Study (section 4.2.6). As for the reconstructed maps, they were compared to the source map using a bidimensional regression analysis based on Euclidean geometry [301]. We used the true coordinates as independent variables and the coordinates of the reconstructed map as dependent variables.

5.2.7 PROCEDURE

The experiment was composed of two sessions, each of which lasted approximately two and a half hours. During the first session (training only), participants were explained the basic features of the application and were explained how to pan and zoom using the two interfaces. During the second session (evaluation session per se), participants had a brief training period before performing the test. The following tables summarize how both sessions were organized (Table 5.4 and Table 5.5) and a detailed description of the training trials is provided in Appendix C.

The order of presentation of the interfaces was counterbalanced within and between the sessions. For the evaluation session, two different maps were used and their order was also counterbalanced (half of the participants explored Map 1 first, and half explored Map 2 first).

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[68] See Chapter 3, 6.1.2 for an explanation regarding the choice of the questionnaire.

Table 5.4. Description of the procedure for the first session (training)

Training Session	
Introduction	Explanations concerning the goal and organization of the experiment. Consent form + photo/video authorization form. Questionnaire 1 (user's profile). Clock face test[69].
Pan & Zoom	Explanations concerning panning and zooming using three tactile maps of different sizes and one tactile frame moved over a large map.
Basic features	Selection, voice commands ("*List*", "*Scale*" and "*Repeat*"), centering – 3 trials[70].
For each interface	Panning – 4 trials. Zooming – 4 trials. Panning and Zooming – 4 trials.

Table 5.5. Description of the procedure for the second session (evaluation).

Evaluation Session	
Introduction	Reminder of the aim of the experiment.
Pan & Zoom	Reminder of the concepts of panning and zooming.
Commands	Selection, voice commands ("*List*", "*Scale*" and "*Repeat*"), centering – 2 trials.
For each interface	Training – 7 trials. Test – 8 trials. Map reconstruction. SUS and NASA-RTLX questionnaires. Questionnaires 2 (comprehension) and 3 (usability).
Debriefing	Questionnaire 4 (users' preferences and comments).

5.3 RESULTS

5.3.1 NAVIGATION PERFORMANCES

SUCCESS

Out of the 128 trials, 115 were performed without the help of the evaluator and considered as successful. Out of the 13 unsuccessful trials, there was 1 *Pan*, 10 *Zoom in* & *Pan,* and 2 *Zoom out* & *in* trials. *Zoom in* & *Pan* trials mainly failed because participants got disorientated; one participant

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[69] Clock face test: we ensured participants knew how to interpret directions given using the clock metaphor. We asked them to point on a raised-line clock-face the ticks corresponding to hours given by the evaluator. Participants also had to explore a raised-line map with three landmarks and to answer questions such as "I am in A. Where is B?" using clock directions.

[70] Training: For Session 1 and Session 2 training trials, participants had to find a target and were then asked a series of questions concerning the position of the target with respect to other landmarks. In that way, we ensured that participants not only performed the action properly, but also understood what the actions meant in terms of map manipulation/exploration. If an incorrect answer was given, explanations were given.

misunderstood the instruction; one participant forgot to zoom in to the Village level, and therefore could not find the target. Two *Zoom out* & *in* trials failed because participants did not manage to correctly perform the required sequence of actions (zooming out, panning, centering, and zooming in). The following table gives the percentage of success according to each type of trial and interface (Table 5.6).

Table 5.6. Percentage of successful trials for each type of trial and interface.

Type of trial	Keyboard	Sliders	Total
Zoom in (N = 16)	100 %	100 %	100 %
Pan (N = 16)	93.8 %	100 %	96,9 %
Zoom in & *Pan* (N= 16)	62.5 %	75 %	68.7 %
Zoom out & *in* (N = 16)	100 %	87.5 %	93.7 %

COMPLETION TIMES

Similarly to the first study, we measured the time spent between the beginning of the trial and the moment when the last target was displayed. To compute mean completion times, we discarded unsuccessful trials.

Zoom in trials were performed faster than other trials, while *Zoom out* & *in* trials tended to take longer than other trials, especially with the Sliders (Figure 5.9, left). Figure 5.9 (right) shows pairwise comparisons between interfaces, expressed as ratios of mean completion times (Sliders / Keyboard). Given the fact that interval endpoints are about seven times less plausible than the point estimate [44], it seems that participants performed faster with the Keyboard than with the Sliders (Figure 5.9, right). However, because the CIs are relatively long, we do not have a precise estimation of how large the effect of the interface on completion times is, but it ranges from zero effect to strong effect (up to 2 times longer). This general tendency was confirmed by the mean ratio of completion times (Sliders / Keyboard), computed across all types of trial, which was 1.3, 95% CI [1.0, 1.7].

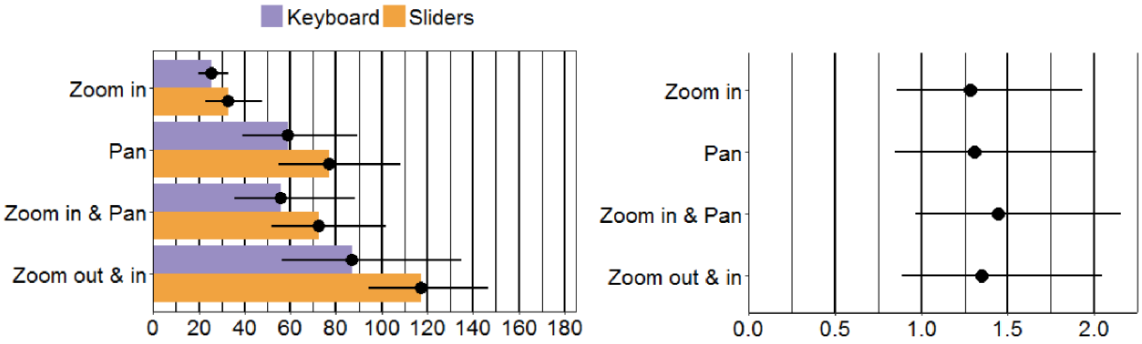


Figure 5.9. Left: mean completion times (in seconds) for each type of trial (N = 8). Right: mean ratios of completion times (Sliders / Keyboard, N = 8). Values superior to 1 indicate larger times for the Sliders than for the Keyboard. Error bars show 95% CIs.

DISTANCE PANNED

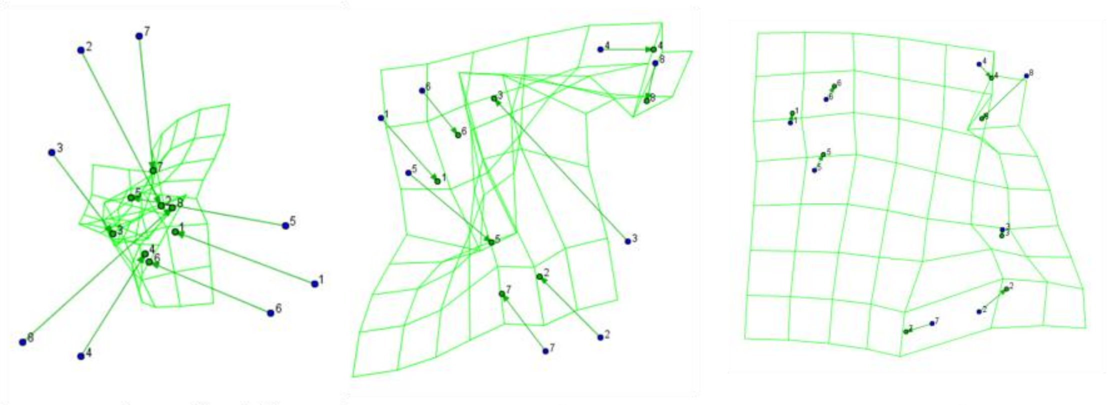
For each type of trial (except *Zoom* trials that did not require panning), we computed the ratio between the total distance panned (in kilometres) and the optimal distance[71]. Overall, participants panned much larger distances than required (Keyboard: *ratio* = 5.2, 95% CI [2.6, 11.2]; Sliders: *ratio* = 5.6, 95% CI [3.5, 9.7]). In addition, participants panned larger distances with the Sliders than with the Keyboard, as shown by the mean ratio between distances panned (Sliders / Keyboard), which was 4.0, 95% CI [-0.6, 8.5].

5.3.2 MENTAL REPRESENTATIONS

BIDIMENSIONAL ANALYSIS

We report results about the bidimensional regression coefficient, which varies between 0 and 1 where 1 indicates the highest degree of similarity between the source map and the reconstructed map (see Figure 5.10 for examples).

Regardless of the interaction techniques, 6 out of 16 maps were highly similar to the source map (*regression coefficient* > 0.8) and 8 were relatively similar to the source map (*regression coefficient* between 0.6 and 0.8). Only two maps strongly differed from the source map (P2 with the Keyboard; P8 with the Sliders), as shown in Figure 5.11. Five participants reconstructed maps whose regression coefficient was superior to 0.8 (P1, P3, P4, P5 and P6). All participants reconstructed at least one map whose regression coefficient was superior to 0.6.



regression coeff. = 0.24
(P2, Keyboard)

regression coeff. = 0.76
(P7, Sliders)

regression coeff. = 0.95
(P3, Keyboard)

Figure 5.10. Three examples of maps interpolation, based on the bidimensional regression analysis[72]. Arrows represent displacement vectors between the source map and the reconstructed map.

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[71] Optimal distance was computed for each type of trial, based on possible paths with the Keyboard. For *Pan* trials, we used the average distance between the targets and the points of reference. For *Pan* and *Zoom in* & *Pan* trials, we computed the optimal distance for the worst-case scenario, i.e. in the case where the users did not choose the right direction (which had to be chosen randomly).

[72] Images were generated using Darcy, a software for bidimensional regression analysis: http://thema.univ-fcomte.fr/16-categories-en-francais/cat-productions-fr/cat-logiciels-fr/294-art-darcy

We computed the mean regression coefficient for each participant: two participants performed relatively poorly (P2 and P8, *mean regression coefficient* < 0.50); five performed well (P1, P3, P4, P6, P7, *mean regression coefficient* between 0.70 and 0.85), and one performed very well (P5, *mean regression coefficient* > 0.95). Participants who did not perform well with one interface (*regression coefficient* < 0.4) did not obtain very high scores with the other interface either (*regression coefficient* < 0.65). On the contrary, participants who performed well with one interface tended to obtain similar scores with the other interface. This was particularly true for P5 who performed extremely well with both interfaces (*regression coefficient* > 0.95).

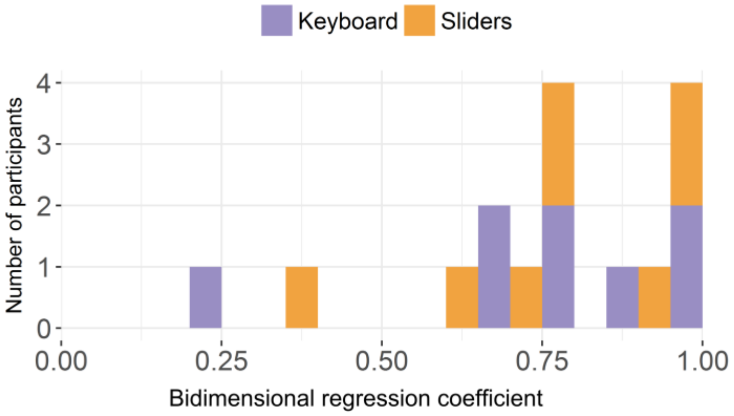

Figure 5.11. Histogram of regression coefficients computed from a bidimensional regression analysis, for the 16 maps reconstructed by the participants. The higher the regression coefficient, the more similar the reconstructed map and the source map are.

Results were similar for the two interfaces (Keyboard: *regression coefficient* = 0.74, 95% CI [0.54, 0.85]; Sliders: *regression coefficient* = 0.76, 95% CI [0.58, 0.87]). For each participant we computed the difference of regression coefficients between the two interfaces (Sliders minus Keyboard). The mean difference was 0.02, 95% CI [-0.12, 0.17]. Differences were not consistent across the participants (half of them obtained better scores with the Sliders, the other half with the Keyboard).

MULTIPLE CHOICE QUESTIONS

For each question, the chance level was 1/4 = 25 %. Overall, the percentage of correct answers was reliably above the chance level (Keyboard: *score* = 63.7, 95% CI [56.6, 72.3]; Sliders: *score* = 56.2, 95% CI [44.9, 66.8], see Figure 5.12, left). Figure 13 (right) shows pairwise comparisons between the two interfaces (Sliders minus Keyboard). It shows that participants tended to perform slightly better with the Keyboard than with the Sliders (*mean difference* = -7.4, 95% CI [-13.7, -3.9]), in particular for Distance and Simple questions.

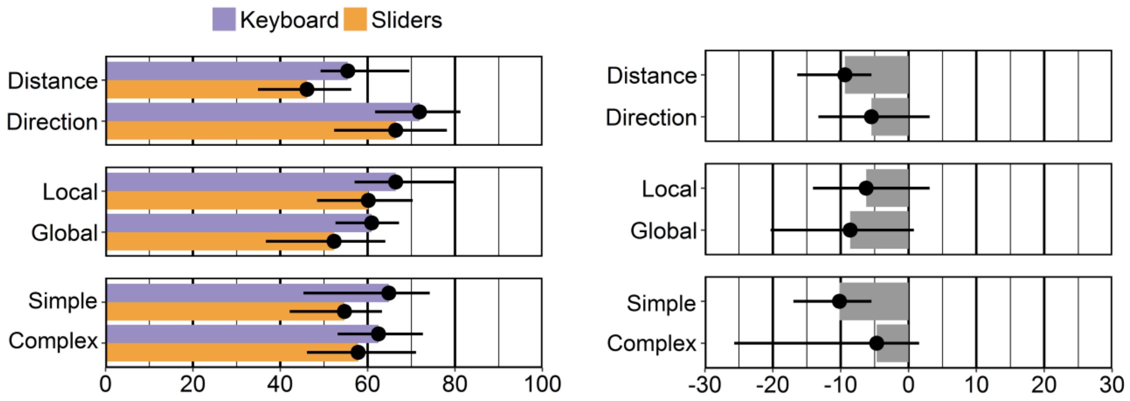

Figure 5.12. Left: percentage of correct answers for each type of questions, per interface (N = 8). Right: mean differences of percentage of correct answers between interfaces (Sliders minus Keyboard, N = 8). Negative values indicate that the percentage of correct answers is higher for the Keyboard than for the Sliders. Error bars show 95% bootstrap CIs.

SUBJECTIVE COMPREHENSION AND MEMORIZATION STRATEGIES

Participants were asked to report on a 5-point Likert-scale whether they thought that they had understood the map. Three participants answered 4 or 5 for both interfaces (P1, P5, P6). Two participants (P4, P7) answered 3 for both interfaces. P2, P3 and P8 respectively answered 3, 3 and 2 for the Keyboard and 2, 4 and 3 for the Sliders. Overall, the median was 3.0 for the Keyboard and 3.5 for the Sliders.

Six participants tried to memorize the landmarks with respect to the cities. P2 said that she used the four cardinal points. P8 said that he remembered landmark locations relative to one another. P8 also said that he tried to remember the path he had navigated to find the targets as well as how he had explored them.

5.3.3 QUESTIONNAIRES AND PREFERENCES

The average SUS score was 76.9 for the Keyboard (95% CI [68.1, 83.7]), and 72.8 for the Sliders (95% CI [60.6, 82.2]), showing very little difference between the two techniques in terms of perceived usability. Results from the NASA-RTLX questionnaire show that the task was mentally demanding and that it required a relatively sustained effort (Figure 5.13, left). Pairwise differences computed for each dimension (Sliders minus Keyboard) did not reveal any reliable difference between the interfaces (Figure 5.13, right).

Concerning the preferences, six participants out of eight found the Keyboard more efficient; five found the Keyboard more pleasant to use, and five chose the Keyboard interface as their best choice overall.

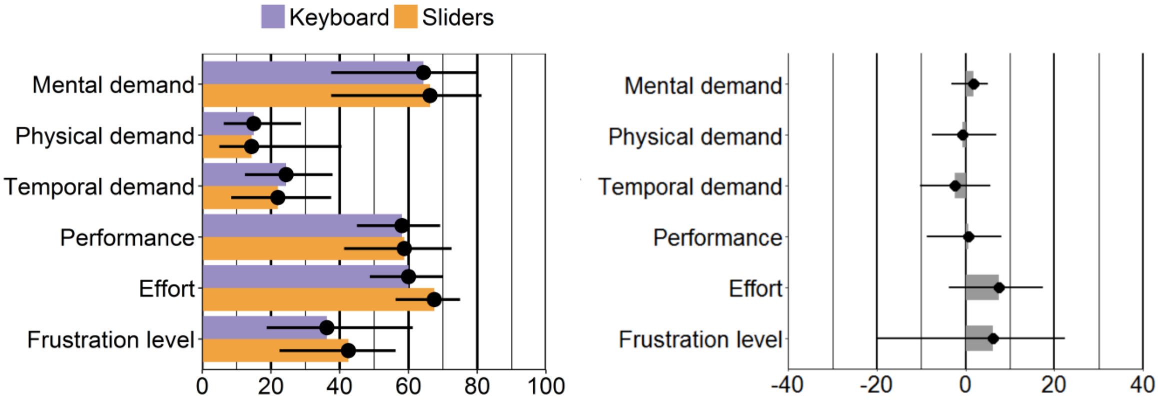

Figure 5.13. Left: Mean workload (max: 100) for each dimension of the NASA-TLX questionnaire (N = 8). Right: For each dimension, mean differences between the interfaces (Sliders minus Keyboard, N = 8). A positive value indicates that participants rated the dimension higher for the Sliders than for the Keyboard. Error bars show 95% bootstrap CIs.

5.3.4 OBSERVATIONS

Several participants expressed having difficulty moving the viewport as they intended, especially for *Zoom in* & *Pan* trials. This was particularly true with the Keyboard interface: when the viewport was too far away, participants had difficulty in knowing which key they had to press in order to reduce the distance.

When using the Sliders for panning, some participants experienced difficulties in understanding how to interpret their position, especially at the beginning of the first session. In addition, on several occasions participants misused the sliders when they had to pan a large distance. For example, if they had to move the viewport towards the right, they would first place the slider far to the left, as one would do for "clutching": by doing so, they thought that they will be able to pan larger distances but it only resulted in moving the viewport in the opposite direction. Furthermore, with the Sliders, only a few participants took advantage of *continuous* zooming by deliberately selecting the most appropriate scale.

Despite these difficulties, which sometimes led participants to feel lost, on several occasions participants managed to recover from disorientation by developing suitable strategies. For example, P1, P3 and P8 zoomed out to the City level in order to relocate a particular City before finding a specific town and then the village they were looking for. P5, during the first session, spontaneously used the "center" feature in order to successively display two Towns at the City level and compare distances. Certain participants also used the "cancel" feature to relocate themselves.

Finally, it should be noted that all participants acknowledged at least once to thinking that they were moving the map instead of the viewport. Participants were mentally visualizing the landmarks around the table and therefore tried to "bring them back" inside the viewport by dragging the map towards them.

5.4 DISCUSSION AND SUMMARY OF STUDY 2

5.4.1 VISUALLY IMPAIRED USERS CAN UNDERSTAND "PAN & ZOOM" MAPS

The accuracy of the reconstruction and the percentage of correct answers (reliably above chance level) indicate that, overall, participants understood and memorized the maps whose exploration required panning and zooming. We did not observe any differences between *Local* and *Global* questions. Most participants stated that they memorized the locations of the towns and villages with respect to their nearest city. Such a strategy probably helped them to answer *Local* questions, which concerned landmarks (towns or villages) that were located around a particular city. In addition, because they had memorized the configuration of the three cities, participants could draw inferences to answer *Global* questions. It should be noted that most of the questions required inferences, as all of the landmarks mentioned in the questions could not be displayed within a single viewport. Hence participants had to combine pieces of information obtained from different viewport positions in order to answer the questions.

Participants answered questions about directions better than distances. We notably observed that they frequently overestimated distances, and several users reported that they found it difficult to estimate distances. In fact, they did not use the "scale" voice command very often and most of them used the zoom slider only as a switch to change the zoom level (e.g. from City Level to Town Level, etc.), and not to select a precise scale (e.g. from viewport representing 200 km to viewport representing 150 km). Altogether, it seems that participants were not comfortable with the concept of scale and rather relied on directions than distances in order to understand and memorize the map. Such results are coherent with empirical studies showing that blind users may need training to correctly estimate distances on tactile maps [314] and that errors in distance judgements are systematic [304].

Taken in a larger context, this result sheds light on visually impaired users' spatial abilities. Difficulties for visually impaired users to correctly integrate various pieces of spatial information into one mental representation have been reported in a number of works and different theories have been proposed to account for these difficulties ([313] for a review). An early one stipulated that visual experience is essential to form mental spatial representations (the "deficiency" theory) but has now been rejected. The "inefficiency" theory states that the lack of visual experience necessarily leads to inefficient (or at least less efficient) spatial abilities. Our results tend to confirm the third theory, called the "difference" theory, which argues in favor of an amodal spatial representation system [173,174]. In this theory, visual experience is not mandatory, and other senses can be used to develop spatial abilities that may be of a different nature than but still as functional as those developed by sighted users. For instance, in our study, one participant, who turned blind when he was four, performed extremely well with both interfaces. In addition, some visually impaired participants spontaneously developed strategies that were similar to those developed by sighted users in Study 1. These results are in line with previous works on geographic maps for visually impaired users (e.g. [45]).

5.4.2 PARTICIPANTS PERFORMED BETTER WITH THE KEYBOARD THAN WITH THE SLIDERS

Participants tended to perform better with the Keyboard interface than with the Sliders interface in terms of navigation (shorter completion times and distances panned) and comprehension (higher percentage of correct answers). Besides, six participants out of eight found the Keyboard interface more efficient. Two explanations can be considered. Firstly, in terms of navigation, the viewport could be moved diagonally by pressing one key only with the Keyboard interface, but with the Sliders interface the two sliders had to be moved simultaneously, resulting in a more complex set of actions. In Study 1, blindfolded participants also panned larger distances with the Sliders than with the Keyboard interface. In fact, even though participants were told to move the sliders for panning and then wait for feedback concerning the position of the viewport, some of them continuously moved the sliders, which resulted in incoherence between the feedback and the actual position of the viewport. This may have led participants to move the sliders too far and therefore to pan larger distances than necessary. Such an issue could be addressed by providing shorter feedback at a higher frequency. Also, the system could provide haptic or tactile feedback when the users move the sliders, which would help them estimate the distance they are moving the viewport.

In addition, the Sliders interface required users to rely on the *absolute* position of the viewport, a metaphor that users were not familiar with, as shown by incoherent uses of the sliders such as trying to perform “clutching” actions. However, five participants out of eight reported that the position of the sliders used for panning helped them to understand which part of the map was being displayed, which illustrates the potential usefulness of the sliders. Further training with the Sliders would certainly have been beneficial in helping participants be more comfortable with the concept of the absolute positioning of the viewport over a fixed map.

More generally, we compared two models for panning and zooming: *discrete* (with Keyboard) vs *continuous* (with Sliders). Participants who preferred the Keyboard reported that they found it easier to pan with step-by-step movements. As for zooming, none of the participants mentioned a preference for one interface over the other. Unlike the sighted users in Study 1, very few participants used the slider for *fine* scaling (adjusting the scale within a given zoom level). However, it is unclear whether this was due to a lack of training or to the fact that selecting a more specific scale was not necessary to correctly perform the tasks. In addition, visually impaired users are very familiar with keyboards, which provide *discrete* control, but rarely have access to input devices or interfaces that provide *continuous* control (such as sliders). This may also explain the advantage of the Keyboard over the Sliders.

5.4.3 PARTICIPANTS MANAGED TO PAN AND ZOOM BUT SOMETIMES FELT DISORIENTATED

Although more than 90% of the trials were successfully performed by the participants, data indicates that some participants experienced difficulties navigating the map, especially for *Zoom in* & *Pan* trials. We consider two potential explanations: users may have had difficulties in interacting with the Keyboard or the Sliders; users may have had difficulties in carrying out efficient strategies.

Data collected during the two studies provides evidence against the first explanation, stating that participants had difficulties in manipulating the Keyboard or the Sliders. The results from the first study, conducted with blindfolded participants, show that both interfaces enabled users to efficiently navigate the map in order to display and select specific targets. Similarly, during the training sessions of the second study, all visually impaired users managed to easily display specific landmarks when they were given their direction, distance and corresponding zoom level. Therefore, when participants were not engaged in a task that was cognitively demanding they were able to interact with the Keyboard or the Sliders to correctly move the viewport or change the zoom level.

The second possible explanation is that participants may have had difficulty in carrying out efficient exploration strategies. In particular, for *Zoom in* & *Pan* trials, which required a complex set of actions, participants had to move the viewport around the point of reference to find surrounding landmarks. This proved difficult for several participants, especially with the Keyboard interface. For instance, they were going too far away from the point of reference, or they did not manage to systematically explore the map around the point of reference. This could be due to insufficient training or to the nature of feedback. The current position of the viewport was always provided with respect to its initial position, both in terms of distance and direction, therefore, participants had to combine these two pieces of information in order to determine the current viewport's position and to decide which action to take. By focusing on one piece of information only (distance or direction), they may involuntarily move the viewport too far away (or too close) or in the wrong direction. As for zooming, it seems that participants were able to choose the correct level whenever necessary.

Overall, it seems that additional training would help users interpret the feedback. Alternative ways of giving feedback about the viewport's position could also be considered, such as providing a tactile overview of the map on which a tactile viewport would move (see 7.4.3), or providing x- and y- coordinates (e.g. "100 km left, 200 km up") instead of polar coordinates (distance and direction).

5.4.4 RELATION BETWEEN NAVIGATION AND COMPREHENSION PERFORMANCES

Unsurprisingly, subjects who experienced navigation issues with one interaction technique were more likely to reconstruct the maps incorrectly: P2 and P4 panned excessive distances with one of the two techniques (resp. Keyboard and Sliders), and their performance for map reconstruction was noticeably lower for the said technique. However, being able to correctly manipulate the interfaces did not systematically lead to good performances in terms of comprehension: P8 navigated very well but had the lowest regression coefficients. Nevertheless, in general, participants who reconstructed accurate maps obtained good performances in terms of navigation, which suggest that navigation skills are necessary but not sufficient to build accurate mental representations.

Results from the bidimensional regression analysis indicate that the majority of participants performed in a similar manner with both interfaces, which argues in favor of the importance of spatial skills, independent of the interface being used. If participants were able to build and manipulate map-like (allocentric) mental representations, they were likely to understand the maps with both interfaces, as far as they understood how to correctly interpret feedback concerning the viewport's position. For example, all blindfolded participants of Study 1 obtained good results with both interfaces. Similarly, P5, who made the most accurate reconstructions and had the highest number of correct answers, was able to perform equally well with the two interfaces.

The question then arises as to why inter-individual differences can be observed. Participants' characteristics collected with the demographic questionnaire did not account for differences in spatial abilities: six participants reported having excellent mental representations (5/5) and two considered theirs to be neither good nor bad (3/5); all had been exposed to maps at school on several occasions but were not using maps anymore because of a lack of availability; participants' age was not correlated with performance. In addition, results were neither correlated with the age at onset of blindness nor with the degree of blindness (residual vision or not): in fact, P8, who turned blind at 17, and P2, who has residual vision, were the least successful. On the contrary, P5, who can be considered as early blind and do not have residual vision (onset of blindness at 4 years old), made the most accurate reconstructions.

Interestingly, P2 and P8 each reported strategies of memorization that were different from other participants: P2 used cardinal points and P8 tried to remember the path he had followed to find the landmarks. Therefore, memorization strategies could better explain inter-individual differences than visual status (early or late blind) could, which argues in favor of the theory of amodal spatial representations. Although these observations are qualitative and subjective, they may indicate that particular strategies of memorization must be encouraged when teaching visually impaired users how to explore and understand "pan & zoom" maps. Such an explanation is in line with previous research work demonstrating the importance of teaching visually impaired users how to develop efficient strategies for retrieving or encoding spatial information [14,211,314].

5.4.5 NON-VISUAL PANNING AND ZOOMING IS COGNITIVELY DEMANDING

The results show that visually impaired people, regardless of their age at onset of blindness, are able to build and manipulate mental images of "pan & zoom" maps, but results from the NASA-TLX questionnaire as well as observations also show that the task is cognitively demanding. This is consistent with literature on panning and zooming for sighted users. Bederson stated that "there is the potential that ZUIs [Zoomable User Interfaces] tax human short-term memory because users must integrate in their heads the spatial layout of the information" [11]. This is especially true with haptic exploration that imposes sequential exploration within the viewport, and therefore makes further demands on short-term memory. Cognitive load was also certainly affected by the task itself (participants had to memorize both the names and configuration of many different landmarks) and by the fact that participants had to manipulate unfamiliar interfaces. Despite the training session, they were also not familiar with the concept of panning and zooming and surely had to be particularly focused to decide which action to take and how to take it. For example, some participants would sometimes use incorrect words for voice commands or make the opposite action of the one intended. Finally, the length of the experiment (2.5 hours in average) probably affected users' performances due to fatigue.

In the following section, we introduce the final study aiming at evaluating the whole system in a more realistic context (a genuine task, and independently moving robots). We specifically designed four additional features that could help users to better understand where the viewport is and navigate better, which would release cognitive resources.

6 STUDY 3: REALISTIC TASK AND INDEPENDENTLY MOVING ROBOTS

6.1 AIM

To investigate the use of BotMap in a more ecological context, we conducted participatory design sessions during which participants had to plan a journey through Africa using four navigational aids. These aids were designed to prevent users from feeling disorientated. In addition, because robots were moved by the evaluator in the first two studies, we wanted to investigate whether using the system with independently moving robots led to specific usability issues.

6.2 MATERIAL AND METHODS

6.2.1 PARTICIPANTS

Three sighted (S) and three visually impaired (VI) participants took part in these sessions. They were all familiar with the system, either because they took part in Study 1 (S3) or Study 2 (VI1, VI3), or because they took part in pilot tests (S1, S2, VI2). We recruited visually impaired participants who performed relatively well during Study 2 (P5 and P7). Hence we avoided a long training phase and kept the experiment relatively short (the robots' autonomy does not exceed one hour).

6.2.2 INTERFACE AND MATERIAL

We used the same set-up as in the first two studies. We used the Keyboard interface only, which appeared as slightly more usable than the Sliders interface. The map was a map of Africa. The names and scales of the three zoom levels were changed accordingly. There were 6 metropolises (zoom level: Metropolis, scale: 9000 km), 27 cities (zoom level: City, scale: 3000 km) and 127 towns (zoom level: Town, scale: 1000 km). Landmarks were chosen to be equally distributed over the map and so that there could never be more than six landmarks displayed at the same time. Finally, to make the scenario more realistic, the names of the countries were also given and for tourist locations the message "tourist" was played after the name of the country (e.g. "Johannesburg, metropolis of South-Africa, tourist").

6.2.3 NAVIGATIONAL AIDS

We implemented four additional features that users could access with voice commands: "*Home*", "*Where am I?*", "*Where is <name>?",* and "*Go to <name>*". When the "*Home*" feature is triggered, the map is reset to its original position and scale (zoom level: Metropolis), i.e. all metropolises are displayed within the viewport. The "*Where am I?*" feature provides information about the viewport's position with respect to the entire map (e.g. "the viewport is on the upper-left of the map"), followed by information about the nearest landmark(s) of a particular zoom level (name, distance, and direction). At the Metropolis level, only the nearest metropolis is given; at the City level, information about the viewport's position is given, followed by the nearest metropolis and then by the nearest city; at the Town level, information about the viewport's position is given, followed by the nearest metropolis, then by the nearest city, then by the nearest town. "*Where is <name>?"* provides the distance and direction of the corresponding landmark with respect to the last selected landmark (e.g. "with respect to B, A is at 3 hours and 3000 kilometers"). If this landmark is not displayed anymore, information is given with respect to the viewport's center (e.g. "with respect to the viewport's center, A is at 3 hours and 3000 kilometers"). Finally, "*Go to <name>"* enables users to center the map on a particular landmark with the corresponding zoom level (e.g. City zoom level for a city).

6.2.4 TASK AND PROCEDURE

Participants were reminded of the different features of the system and the four navigational aids were explained. They could explore a training map using all of the different commands, until they felt comfortable. They were then given the following scenario and were given 25 minutes to complete the task:

> *"As a reporter, you are making a documentary about social enterprises in Africa. You have already planned to meet three CEOs in three different places (Dakar, Djado and Cairo), but you would also like to go sightseeing. You are therefore looking for one tourist city and one tourist town between Dakar and Djado, and one tourist city and one tourist town between Djado and Cairo. For environmental reasons, you aim to minimize the number of kilometers travelled. Using the interface, find an itinerary that fits all these criteria."*

If participants completed the task in less than 15 minutes, another similar scenario was provided with different destinations. Participants could stop when they were satisfied with their itinerary. Then, a debriefing was conducted in two parts. First, participants were asked to comment upon the navigational aids and the robots, without being guided by any questions. Secondly, they were asked to answer a number of questions. For the navigational aids, they had to give their agreement on two statements using a 5-points Likert scale: How useful the navigational aid was? Is the navigational aid easy to use? They were also asked to comment upon eight robot attributes: discriminability, height, interactivity, shape, speed, stability, noise, number. In addition to these questions, we computed the number of times each navigational aid was used and the time needed for the robots to reach their new positions.

6.3 RESULTS AND DISCUSSION

Apart from VI2, who planned two itineraries within the allotted time, participants planned a single itinerary. On average, participants interacted with the system during 21 minutes (*SD* = 4.2), excluding training. Concerning the robots, they reached their new position in 9 seconds on average (*SD* = 2.8).

6.3.1 NAVIGATIONAL AIDS

All navigational aids were found to be very easy to use (*Mdn*[73] = 5) and very useful (*Mdn* = 5). However, there was a small preference for the *"Where is <name>?"* and *"Go to <name>"* (*Mdn* = 5) features in terms of usefulness, compared to "*Home*" (*Mdn* = 3) and "*Where am I?*" (*Mdn* = 3.5). "*Home"* and "*Where Am I?"* were barely used (respectively 2 times and 5 times across all sessions): participants did not feel disorientated and therefore did not find it necessary to use them. However, they acknowledged that they could be potentially useful. The *"Where is <name>?"* feature was found to be very useful to go from one landmark to another without deviating, to remain orientated and also to estimate distances between two landmarks. Two participants (S3 and VI3) also used it to quickly locate one landmark within the viewport. It was used 76 times across all sessions. *"Go to <name>"* was not used as often (25 times across all sessions): participants mainly used it to go back to one of the three landmarks indicated by the evaluator, without having to pan or zoom, thereby saving time. However, two participants were skeptical about using *"Go to <name>"*, as both the viewport's position and zoom level could be updated at the same time without any explicit feedback.

In addition, four participants mentioned that they would enjoy having additional information on the map (e.g. museums, capitals, etc.) and being able to filter which landmarks to display. Two also indicated that they would like to be able to retrieve a list of landmarks (e.g. tourist towns or museums) near a specific landmark. By doing so, they would only zoom in if the list is not empty or if they wanted more details about a landmark given in the list, which will allow them to save time.

To sum up, participants valued the four navigational aids, and the *"Where is <name>?"* feature appeared to be essential. *"Go to <name>"* was also found to be useful, but additional feedback should be provided to help users understand how the map is updated (viewport's position and zoom level). Participants found the system very comprehensive and stated that the proposed functionalities were sufficient to use it extensively and independently. In particular, the visually impaired users stated that they would like to use it to explore the main points of interest of the city in which they live (VI1), the capitals of the countries of the former USSR (VI2) and the towns and villages in the Pyrenees (e.g. from West to East).

6.3.2 INDEPENDENTLY MOVING ROBOTS

Participants' comments about the robots' attributes were very positive and provide interesting insights about the design of actuated tabletop TUIs for visually impaired users. Concerning the physical properties of the robots, five participants found their *height* ideal (3 cm). Only one indicated that even though their height was not a problem, he would have preferred them to be smaller (S2). All participants found their *shape* ideal, especially because they do not take up a lot of place. Participants found that the robots were sufficiently *stable*, even though some stated that they needed to explore the map carefully (S2, S3, VI2, VI3): greater stability would have been appreciated, but this was not critical. Interestingly, three participants indicated that the *number* of robots used was sufficient and that using more robots would result in the exploration being more tedious and should be avoided. The three others (S2, VI2 and VI3) indicated that more robots

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[73] *Mdn* stands for median.

could be used to display more information. Five participants found the *noise* made by the robots very useful as it helped them to know whether the robots were still moving or whether the system was working. Two participants even mentioned that the noise could be louder, so that participants could be positive that the robots are indeed moving (VI2, VI3). When discussing the *interactivity* of the robots, three participants said that they were very responsive. Two suggested that the robots could also be used as input devices, for example to filter which information to display or to retrieve the names of landmarks within a certain distance. When commenting upon the *discriminability* of the robots, three participants stated that all robots should be similar and that using different sounds or shapes would not at all be useful. Two participants (S1, VI2) suggested that different shapes could be used to help differentiate the robots (e.g. the larger the city, the higher the robot). Finally, none of the participants found the *speed* too slow. However, the three visually impaired participants stated that if the robots could move faster, it would be better, but that the current speed was not an issue (VI1, VI2, VI3).

7 GENERAL DISCUSSION AND PERSPECTIVES

7.1 TECHNICAL IMPLEMENTATION AND REPRESENTATIONS

The current implementation of BotMap enables visually impaired users to access maps composed of several landmarks. Although the robots were not particularly fast, participants found their speed reasonable. Still, using faster robots could be beneficial. To do so, improved algorithms could be used to optimize the assignation of landmarks to robots (e.g. the Hungarian algorithm [151]) as well as their trajectories (e.g. [287]). Faster robots such as Zooids [81] could also be used. Another drawback of the current implementation is that the robots are controlled by specific patterns displayed on the underlying screen and are tracked by a camera placed above the interactive table, leading to a complex set-up. These limitations could be addressed, for example, with the latest Ozobots model[74], which can be controlled remotely using a mobile application, foregoing the need to use an underlying screen. Similarly, Cellulos [223] are hand-held robots that can be used on non-interactive surfaces and that do not require an external camera.

The participatory design sessions provided insights into the use of robots for actuated tabletop TUIs. In particular, different properties of the robots were found as ideal by most participants, notably their height (2.5 cm), shape (2.5 cm wide, circular) and noise (feeble but not silent). Usability could be improved if the robots were heavier or more stable, or could reposition themselves when they are involuntarily moved by the user. Interestingly, the low number of robots used was not seen as critical, and several participants indicated that using a larger number of robots would not be beneficial. Another aspect that would be worth investigating is to use the robots as controls. Although this is already the case with the sliders, giving users the opportunity to directly interact with the robots representing the landmarks could open interesting avenues: for example, one participant suggested that by rotating one robot, the names of its surrounding landmark could be given (i.e. like a radar). The robots could also provide haptic feedback, as the Cellulos do [223]. In could also be interesting to reflect upon how the set of interaction techniques proposed for the Tangible Bots [232] could be adapted to BotMap.

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[74] http://ozobot.com/products/ozobot-evo

The main limitation of using robots to display maps is that only landmarks or dots can be physically rendered. Even though it is possible to render maps of various complexities with dots only, traditional maps are also composed of lines and areas. In Chapter 3, we proposed to use retractable reels as a way of drawing physical interactive lines. A combination of robots and retractable reels could also be envisaged to give visually impaired users access to various types of maps. In addition, the interaction techniques and technologies that we mentioned in the discussion sections of the Tangible Reels (Chapter 3, 8.2) and the Tangible Box (Chapter 4, 6.4) could also be relevant for BotMap (e.g. sonified areas, use of finger-based interactions, etc.). Finally, although in this study we focused on geographical maps, many applications could benefit from the ability to pan and zoom such as graphs with large datasets (e.g. scatter plots, metro maps, sky maps, graphs used in biology and referred to as molecular interaction maps), GUIs for browsing and searching different items (e.g. a virtual music store), etc.

7.2 INTERACTION TECHNIQUES AND PANNING AND ZOOMING MODELS

Both results from Study 1 and Study 2 indicate that the Keyboard and Sliders interfaces enabled users to pan and zoom without vision, with a slight advantage of the Keyboard over the Sliders in terms of navigation performance. Distance and direction feedback proved essential to enable users to locate the viewport, even though training was required to understand how to interpret these pieces of information. Ninety percent of the trials were successfully performed, and results suggest that unsuccessful trials were due to a lack of training or inappropriate navigation or memorization strategies, rather than to the manipulation of the input techniques per se. However, six participants found the Keyboard more efficient than the Sliders, which might indicate that *discrete* panning was preferred to or better than *continuous* panning. As for zooming, participants did not report differences between the two interfaces but only a few took advantage of the possibility to select a *fine* scale within a particular zoom level with the Sliders. Therefore, implementing *continuous* zooming might not be as essential and beneficial as expected. However, these observations may be related to a more frequent use of discrete than continuous pointing devices by visually impaired users.

Based on participant feedback and observations, we identified three aspects of BotMap's design that could be improved. First, some participants had difficulty remembering all voice commands and sometimes used incorrect words. Future versions of the prototype should limit the number of voice commands and some of them could be replaced by physical buttons or tangible interactions. A more appropriate keyboard was also suggested by blindfolded participants, with more space between the keys used for panning and zooming (however, it should be noted that none of the visually impaired users reported issues with the keyboard). Finally, similarly to what is done with visual sliders, the tangible sliders for panning could be improved either by physically representing the whole height/width of the viewport instead of its center only (e.g. with a length-adjustable bar), or by using more precise and easy to use sliders. To help users estimate how many kilometers they are moving the viewport, tactile and/or audio cues could also be added during the sliders displacements.

7.3 MENTAL REPRESENTATIONS

Very importantly, we showed that visually impaired users can understand maps whose exploration requires panning and zooming, regardless of their age and age at onset of blindness. These results are in line with previous studies conducted with blindfolded participants [226] as well as research on zoomable diagrams [248]. One limitation of our second study is that the maps were composed of only ten landmarks and that there were only three zoom levels. However, 160 landmarks were used in the third study; additional work is required to investigate to what extent using a larger number of landmarks and zoom levels would impact comprehension.

The interfaces relied on two different metaphors: the Keyboard did not provide users with any information about the current position of the viewport (relative displacement of the viewport) while the Sliders did (absolute positioning of the viewport). Although we would have expected the Sliders interface to be preferred or to lead to better comprehension scores, as it makes it possible to infer the position of the viewport on the map, participants tended to perform better with the Keyboard interface. As mentioned before, we do not know if this is related to a more frequent use of keyboards by visually impaired users (to navigate a document for example). Therefore, on that topic again, it would be interesting to evaluate the effect of more training on the use of the Sliders interface (which might require a higher level of abstraction), and to investigate whether navigational aids can compensate for the lack of information inherent to the Keyboard interface.

The four navigational aids were found to be very useful and easy to use by the participants, especially the "*Where Is <name>*" feature, which enabled them to remain orientated and also to compute distances between two landmarks. Together with the other voice commands (list, scale, etc.) and functionalities (pan, zoom, center), participants were able to successfully and independently find an itinerary between different landmarks displayed at different zoom levels, which further demonstrated the overall usability of the system. However, as discussed in Study 2, participants' performances appeared to depend on their spatial abilities, and more precisely their ability to generate and/or manipulate survey-like mental representations. In particular, it is interesting to note that the participant with the highest average comprehension score managed to perform very well with both interfaces (comprehension and navigation). We suggest that training could benefit users in terms of comprehension and navigation, and could also help reduce cognitive load.

7.4 PERSPECTIVES FOR FURTHER RESEARCH

In this section we provide a few reflections concerning the improvement of non-visual "pan & zoom" maps for visually impaired users:

7.4.1 DEVELOPING AFFORDABLE AND RELIABLE SYSTEMS.

Better tangible devices are required to increase the accessibility of dynamic maps. One particular challenge is to design robots that are stable in addition to being small, affordable and fast. Speed and ease of use (simple calibration, independent of light conditions, etc.) should also be considered to allow visually impaired users to independently access "pan & zoom" graphical representations. Finally, as well already mentioned, one could consider making tangible and dynamic maps that will not only include points (landmarks) but also physical lines (e.g. boundaries) and/or textured areas (e.g. national parks).

7.4.2 AUTOMATING THE ADAPTATION OF CONTENT.

Due to the limited amount of information that can be rendered tactilely, geospatial data needs to be adapted in order to be accessible. This time-consuming process becomes even more complex when there is a large content, and when each element must be assigned a particular zoom level "by hand". Therefore, further research is needed to facilitate the adaptation of "pan & zoom" maps and could build upon existing non-visual zooming algorithms (e.g. [226,248,269]). In particular, the proposed algorithms should be compliant with the use of open data (e.g. OpenStreetMap) and researchers should propose innovative ways to compensate for the restricted number of landmarks that can be displayed simultaneously. For example, a single robot could represent several landmarks at the same time, and users could locate these landmarks more precisely by zooming in.

7.4.3 REDUCING COGNITIVE WORKLOAD.

Research on visual panning and zooming interfaces has investigated various ways of reducing users' cognitive workload, especially by helping them to better navigate and avoid *desert fog*: use of animations [12], overviews [104], artificial landmarks and cues [92], etc. Although we already proposed a number of navigational aids, further research is needed to design additional features and better evaluate their efficiency in terms of navigation performance, comprehension and satisfaction. In particular, we believe that the use of a tangible viewport inside an overview window (tactile or virtual) could greatly reduce cognitive workload as it will make it unnecessary for the users to mentally visualize the viewport's position, therefore freeing cognitive resources (Figure 5.14). Ideally, this tangible viewport should be actuated: if the users ask the system to "go to" a certain place, the viewport could move to reflect that change and help the users better understand which part of the map is displayed[75]. A design challenge that will need to be addressed concerns the size of the viewport, which should be adjustable to reflect changes of scale; this could be particularly challenging when several zoom levels are provided and when the range of possible scales is large (e.g. from the viewport representing 1000 km to the viewport representing 20 km). A low-cost and alternative solution could be to provide users with a set of tangible frames of different sizes, which they could place and move over a raised-line map to pan and zoom.

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[75] At the very beginning of this project, we did in fact reflect upon the design and development of such a tangible and actuated viewport but decided to focus on more regular interaction techniques (the Keyboard and the Sliders), which are more likely to be used outside laboratories.

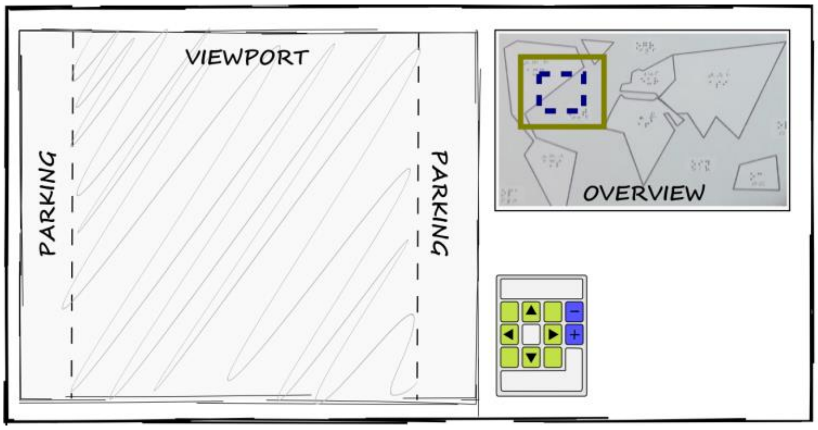

Figure 5.14. A sketch of a tangible viewport (in green) that could be moved over a raised-line map and whose size could be adjusted (in blue) to reflect changes of scale.

8 CONCLUSION OF CHAPTER 5

In this chapter, we described the design, implementation and evaluation of an actuated tabletop TUI that enables visually impaired users to independently explore "pan & zoom" maps. Each landmark is represented by a robot, and whenever the map needs to be refreshed, the robots move to their new position. To interact with the map, we proposed two interfaces, the Keyboard and the Sliders, as well as a number of voice commands and navigational aids. We conducted three user studies. The first, conducted with blindfolded participants, demonstrated that both interfaces can be used to perform panning and zooming operations of various complexities without vision. The second study, conducted with visually impaired users, demonstrated that users can understand maps whose exploration requires panning and zooming, and that they were able to pan and zoom, even though some felt disorientated on occasion and found that the task was cognitively demanding. We discussed a number of factors that may have explained differences in terms of navigation and comprehension, such as strategies of memorization, training, and abilities to build map-like mental representations of space. In the final study, we conducted participatory design sessions during which participants had to plan a journey through Africa using four navigational aids. This study showed the potential of the navigational aids to facilitate navigation and reduce cognitive load, and gave interesting insights into the design of actuated tabletop TUIs for visually impaired users. We concluded the chapter by discussing to what extent the prototype could be improved, notably in terms of implementation and interactivity, and proposed the use of a tangible viewport to further facilitate the exploration of "pan & zoom" maps by visually impaired users.

CHAPTER 6

DISCUSSION AND PERSPECTIVES

J'ai adopté exprès un ton sec et péremptoire pour leur faire peur et leur faire comprendre que j'ai d'autres possibilités, que je n'ai évidemment pas, afin qu'elles paraissent plus grandes et pour ainsi dire illimitées. Je me suis senti aussitôt mieux, car il n'y a rien de tel que les perspectives illimitées.

Romain Gary (Emile Ajar). Gros-Câlin.

Chapter structure

Throughout this thesis, we aimed to investigate how to improve maps and diagrams for visually impaired users by making them not only interactive, but also tangible (i.e. physical and reconfigurable). Given the lack of research on non-visual TUIs, we chose to explore the design space of tangible maps and diagrams for visually impaired users by designing, developing and evaluating three prototypes (the Tangible Reels, the Tangible Box, and BotMap), which allowed us to cover several research questions. In this chapter, we first review the contributions of this thesis by reframing them within these research questions, and discuss the scope of this thesis. Then, as we already discussed the contributions and limitations of the three projects in the corresponding chapters, we discuss their relevance at a higher level by relating them to other fields of research. Finally, we consider a number of perspectives for further research.

1 THESIS SUMMARY AND CONTRIBUTIONS

In Chapter 1, we listed the main research questions of this thesis, which were respectively related to: 1) the benefits and limitations of using TUIs compared to current practices and existing approaches; 2) the design of tangible maps and diagrams for visually impaired users; 3) the tasks and representations supported by tangible maps and diagrams; 4) the usability of the proposed TUIs. In this section, we provide a summary of our contributions, according to these research questions.

1.1 BENEFITS AND LIMITATIONS OF TANGIBLE MAPS AND DIAGRAMS FOR VISUALLY IMPAIRED USERS

1.1.1 WHAT ARE THE CURRENT PRACTICES AND WHAT ARE THEIR BENEFITS AND LIMITATIONS?

In order to better understand why there is a need to improve or complement current practices, we first reviewed a number of techniques that are currently used to make maps and diagrams accessible to visually impaired users (Chapter 2, Part B). On the one hand, *static tactile graphics* encompasses, for example, raised-line as well as 3D-printed maps and diagrams. As suggested by the category's name, these graphics are mainly characterized by the fact that they cannot be updated. On the other hand, some tactile graphics can be constructed on a corkboard or on a magnetic board, making them reconfigurable. However, these *updatable tactile graphics* are not interactive, which makes them difficult to be independently used by a visually impaired person. Overall, traditional tactile graphics can be explored using both hands–a type of exploration that provides a number of benefits (Chapter 2, Part B, 5).

1.1.2 WHICH APPROACHES HAVE BEEN CONSIDERED BY RESEARCHERS AND WHAT ARE THEIR BENEFITS AND LIMITATIONS?

To answer this question, we reviewed the literature concerning research projects of interactive maps and diagrams (Chapter 2, Part C). To do so, we proposed a new classification [50], with the aim of delivering a structured overview of the field, as, despite a large number of projects, we observed a lack of a common terminology to refer to the different approaches that have been proposed. We distinguished between *digital* maps and diagrams, which do not rely on a physical representation and are usually limited to one or two points of contact, and *hybrid* maps and diagrams, which rely on a physical representation that provides multiple points of contact. We illustrated each category and sub-category by a number of examples, and analyzed each category along four aspects: cost and availability, factors impacting exploration, content and updatability. We hope that this classification and systematic comparison will help researchers better apprehend the specificities of each approach and, eventually, better identify the limitations that need to be overcome.

This literature review highlighted the fact that updatable and interactive maps and diagrams were mainly digital, with a very few exceptions of hybrid prototypes that are either very expensive (e.g. raised-pin displays [350]) or extremely slow (see Linespace [292]). Therefore, we pointed out a lack of research concerning the development of updatable and hybrid maps and diagrams. In addition, we also observed a lack of interest for TUIs for visually impaired users, despite the fact that TUIs inherently provide a certain level of updatability and support two-handed exploration.

1.1.3 WHAT ARE THE KNOWN BENEFITS OF TUIS AND TO WHAT EXTENT MAY THESE BENEFITS BE RELEVANT TO VISUALLY IMPAIRED USERS?

We were interested in two inherent properties of TUIs [113]: 1) as digital information is physically embodied, TUIs can be explored using both hands and provide multiple points of contact; 2) the representation can be reconfigured by manipulating or moving the tangible objects. Throughout the development of three tabletop TUIs, we demonstrated that tangible maps and diagrams for visually impaired users could take advantage of these characteristics. During the user studies that we conducted, we observed that participants took advantage of the possibility to explore the representation with both their hands, for example, to get an overview of the representation or to estimate distances between two elements. In addition, we considered a number a tasks relying on the reconfigurability of the interfaces, such as the (re)construction of diagrams (Chapter 3) and the exploration of “pan & zoom” maps (Chapter 5).

Another advantage of TUIs is that they provide a double interaction loop [305]: by touching and manipulating the tangible objects, users get an immediate feedback; then, feedback is provided through the intangible representation. The benefits of this first feedback loop for visually impaired users are self-evident. For example, during the first evaluation of the Tangible Reels (Chapter 3, 3), participants were asked to explore a map that was not interactive and the haptic feedback provided by the tangible objects was sufficient to enable users to understand the map layout. However, concerning the second interaction loop, the use of audio feedback instead of visual feedback can be an issue, notably due to the transient nature of verbal feedback. For example, with BotMap, we observed that audio feedback concerning the viewport’s position was not always consistent with the actual position of the sliders, which confused the users. In section 4.1.2, we discuss a number of approaches that could improve audio feedback.

The literature review also highlighted potential benefits of TUIs for (collaborative) learning (e.g. [137,188,271]). With the educational workshop based on the Tangible Reels and the development of the Tangible Box, we demonstrated that TUIs do have a strong potential for visually impaired students as well, notably because they may support a large range of activities that require students to (physically) play an active role in the learning process. With the Tangible Reels, we also began to investigate how the prototype could be used in a collaborative situation, by suggesting that each user could own a tangible object that would enable them to annotate the map

(Chapter 3, 8.4). Later on in the chapter (4.2), we discuss challenges that remain to be faced when designing collaborative TUIs for visually impaired (and sighted) users.

1.1.4 What are the inherent limitations of TUIs and are there further limitations specific to TUIs for visually impaired users?

In Chapter 2, Part D, 2.5, we listed a number of limitations of TUIs, among which the use of tangible objects that can be lost or damaged over time and that need to be stored when not in use [276]. TUIs are also limited in terms of scalability and versatility. Throughout the design of the TUIs, we faced similar challenges. However, issues of scalability for visually impaired users are especially important as the tangible representation cannot always be enhanced with visual feedback. Audio feedback can be used but cannot convey as much information as visual feedback, and is more sequential. Finally, we mentioned some limitations of tangible maps and diagrams that are more related to the properties of touch than to the use of TUIs themselves. For example, whereas it is possible for sighted users to instantly get an overview of the number of tangible objects at their disposal, visually impaired users first need to scan the table with their hands to locate them, which takes longer.

1.2 Designing tangible maps and diagrams for visually impaired users

1.2.1 What are the design challenges specific to TUIs for visually impaired users?

To address this question, we first discussed in Chapter 2, Part E, 2 several aspects that should be taken into account when designing tangible maps and diagrams for visually impaired users. This theoretical list was gradually completed, throughout the exhaustive review of the literature that we provided in section Chapter 2, Part E, 4 and the design of the three TUIs. Concerning the tangible objects, several aspects must be taken into account: the most important one is probably the stability of the objects, followed by the fact that the tangible objects should convey sufficient information to enable users to access relatively complex and expressive maps and diagrams. The tangible objects should also be easily identifiable, for example using irregular forms [196], and they should always be coupled with the digital representation. These aspects, although they may have been addressed during the development of TUIs for sighted users, appeared particularly crucial for visually impaired users.

The design of suitable interaction techniques is also essential, not only for the interface to support a variety of tasks such as reconstructing, editing or exploring a map or a diagram, but also to compensate for the absence of vision. In particular, there is a need to design interaction techniques that enable users to quickly locate or reposition tangible objects [192]. Feedback is specifically relevant as it must enable users to understand the current state of the system and of the tangible objects (e.g. are they properly tracked by the system?) [196]. The question of how to switch between the different modes supported by the interface is also important as the design of non-visual (and tangible) menus can be particularly challenging.

In addition, designers should try as much as possible to provide both a tangible representation and a visual representation on which low-vision and sighted users can rely (“bi-graphism”). All these design aspects must be addressed while keeping in mind the importance of using technologies that are affordable but also reliable, notably for tracking the tangible objects, as it may be difficult for visually impaired users to detect when an object is incorrectly tracked.

1.2.2 HAVE THESE DESIGN CHALLENGES BEEN ADDRESSED IN THE LITERATURE, AND IF SO, WERE THE PROPOSED SOLUTIONS SATISFYING?

In Chapter 2, Part E, 4, we described in detail eight prototypes of tangible maps and diagrams and discussed to what extent they took into account the aspects previously mentioned. We showed that not only have a number of design challenges been rarely considered, but also that when they were, the solutions were not systematically evaluated by visually impaired users. We also emphasized that despite the fact that several interaction techniques for the (re)construction or edition of maps and diagrams were designed, very few were thoroughly implemented. Overall, it is therefore very unclear whether the proposed solutions were feasible and usable. In addition, we observed that most prototypes supported specific graphical representations only (e.g. itineraries composed of a sequence of routes [272]) and it seemed difficult to adapt them to other types of maps and diagrams or to more complex representations.

1.2.3 HOW TO ADDRESS DESIGN CHALLENGES FOR WHICH NO SUITABLE SOLUTIONS HAVE YET BEEN PROPOSED?

With the development of the Tangible Reels, the Tangible Box and BotMap, we addressed several design challenges by providing a number of technical solutions and interaction techniques. We hope that they will help researchers (and possibly teachers and designers) overcome the difficulties that are most often encountered when developing TUIs for visually impaired users. To do so, we described in detail the design rationale of the three interfaces and conducted user studies with visually impaired users. Once again, we already discussed the limitations of the three prototypes as well as their benefits over existing prototypes in the corresponding chapters.

We addressed the question of the stability of the tangible representation by proposing two types of tangible objects: the Tangible Reels (Weights and Sucker Pads, see Chapter 3, 2), and the Tangible Box's objects, composed of two magnets (Chapter 4, 2.1). We assessed the stability of the Tangible Reels throughout two user studies and one educational workshop; although they would benefit from being smaller, the use of sucker pads or cylinders filled with lead proved promising. As for the magnetic-based tangible objects, they offer a more limited way of interaction as they cannot be lifted off the surface, but they present the advantage of being small, cheap and very easy to assemble. In addition, we discussed in Chapter 5 how to ensure the accuracy of the tangible representation by using actuated tangible objects that can move back to their correct position whenever they are involuntary moved. Although such an approach is not as satisfying as providing users with a stable tangible representation, it is an interesting alternative when the tangible representation needs to be updated by the system.

To allow for expressive and/or complex tangible maps and diagrams, we investigated three different approaches. With the Tangible Reels, we used retractable reels, which allow the construction of lines of various lengths using a single type of object (as the literature review revealed a lack of feasible, usable and scalable solutions for constructing lines of different lengths [261,272]). With the Tangible Box, we relied on the idea of dividing functionalities accordingly, as suggested by McGookin et al. [196]. The tangible objects can be used to enhance traditional static supports such as raised-line maps or German film, therefore taking advantage of their potential complexity and expressiveness while making them interactive and updatable. Finally, with BotMap, we demonstrated that actuated tangible objects can be used to enable the exploration of large information spaces, through panning and zooming.

Furthermore, we described the design of various interaction techniques and feedback. With the Tangible Reels, we proposed a procedure that enables users to construct lines that are coupled with their digital counterpart (while existing solutions did not all ensure this coupling). We also proposed a two-step guidance technique that allows visually impaired users to quickly position a tangible object in its right place. Although this technique was designed for the Tangible Reels, it could be adapted to any interface that requires visually impaired users to position tangible objects in a specific place. In Chapter 3, 4, we also described in detail the procedure and instructions for the reconstruction of tangible maps and diagrams, as well as an initial investigation of two interaction techniques for the construction and vocal annotation of tangible maps and diagrams. With BotMap, we described the design of two interfaces that enable visually impaired users to pan and zoom, one of which relying on the use of tangible sliders.

Finally, for the three interfaces, we proposed interaction techniques for the exploration of the tangible representation. As the technique proposed for Tangible Reels was not fully satisfying (participants found the gesture difficult to perform), we designed a different technique for BotMap, based on the tracking of a fiducial marker attached to one of the user's fingers. This technique proved very usable, although it requires the use of an external camera. For the Tangible Box prototype we investigated the use of a tangible object that acts as a "selection tool" and suggested certain techniques for interacting with tangible objects and tangible menus. However, at the time of writing, the usability of these solutions had not yet been assessed.

1.3 DESIGN SPACE OF TASKS AND GRAPHICAL REPRESENTATIONS SUPPORTED BY TUIS

1.3.1 WHICH TASKS CAN BE SUPPORTED BY (OR PARTICULARLY ADAPTED TO) TABLETOP TANGIBLE MAPS AND DIAGRAMS FOR VISUALLY IMPAIRED USERS?

Throughout this thesis, we tried to investigate and illustrate what type of tasks could be supported by tabletop TUIs for visually impaired users. We first analyzed existing prototypes of tangible maps and diagrams for visually impaired users and identified a number of tasks that had been envisaged and/or implemented (Chapter 2, Part E, 4.4). Most of these tasks concerned either the reconstruction of a map with tangible objects with or without guidance instructions (e.g. [196]), or the exploration of graphical representations with (actuated) tangible objects (e.g. [256]).

With the Tangible Reels, whose design was directly inspired by the corkboard and magnetic board construction techniques described in Chapter 2, Part B, 3.2, we mainly focused on the reconstruction of maps and diagrams. With BotMap, we particularly focused on panning and zooming, i.e. a task that required users to manipulate the graphical representation. In the framework of the Tangible Box project, we more precisely investigated the design space of tasks, though in an educational context. To do so, we organized participatory design sessions with specialized teachers (see Chapter 4, 4.1) and, by analyzing their ideas, identified four types of tasks: exploration/manipulation, annotation/edition, construction and reconstruction, which can be considered as the core modules of tangible-based educational activities. We also identified five types of possible activities, which may rely on one or several tasks: exploratory activity, expressive activity, customization, trial and error activity, and evaluation.

Furthermore, during these participatory design sessions, we observed that teachers sometimes had difficulty in proposing educational activities whose mode of interaction would differ from traditional GUIs (such as moving a cursor over a map to retrieve the names of the landmarks). To facilitate the design of activities that would take full advantage of the physicality and updatability of TUIs, we proposed a design framework for the Tangible Box composed of four main themes (overall characteristics, material, activities and interactivity) as well as a list of practical hints (Chapter 4, 4.2). Each theme encompasses a series of aspects that the teachers/developers can vary, or from which they can draw inspiration to design rich and diverse tangible applications. Although this design framework was specifically intended to be used for the Tangible Box and that further work is needed to make it more comprehensive, we believe it can also be used to design tangible (educational) activities for visually impaired users, regardless of the interface used.

1.3.2 HOW COMPLEX/EXPRESSIVE CAN TANGIBLE MAPS AND DIAGRAMS BE?

In Chapter 2, Part E, we observed that existing prototypes of tangible maps and diagrams for visually impaired users mainly supported a single type of graphical representation, of limited complexity (e.g. geometric shapes [119], routes composed of five segments [272], etc.). In addition, when the digital information was more complex, the tangible representation was not very expressive (e.g. [196,256]). By designing specific tangible objects that can be used to make lines tangible or that can be used on top of traditional supports, we demonstrated that tabletop TUIs for visually impaired users can support different types of expressive graphical representations, which can be of various complexities (e.g. clocks, timelines, metro maps, bar charts, etc.). With BotMap, we considered another alternative by implementing non-visual panning and zooming. With this approach, we showed that it is possible to make large interactive spaces accessible to visually impaired users (in the last study of the BotMap project, we used a map of Africa composed of 160 landmarks). Finally, “hybrid” interfaces combining, for example, the Tangible Box with the Tangible Reels would be worth considering (see section 4.1.4 for a short discussion about the possibility of an “all-in-one” interface). In section 4.1.3, we also discuss another approach that we briefly mentioned in Chapter 3, 8.3: providing haptic and/or audio feedback to “virtually” display pieces of information (and notably areas).

On the whole, trying to precisely quantify how complex or expressive tabletop maps and diagrams for visually impaired users can be may not be appropriate, or feasible. However, it seems that on the one hand, tabletop maps and diagrams that do not rely on visual intangible representations cannot reach the complexity of visual representations. And on the other, we believe that the nature and characteristics of the graphical representations that we considered in this thesis clearly demonstrate that there is no reason why tangible maps and diagrams for visually impaired users, although they are inevitably restricted by the use of tangible objects (as TUIs for sighted users), should always be relatively simple and/or unexpressive.

1.4 USABILITY OF THE PROPOSED TUIS

As we already said, existing prototypes of tangible maps and diagrams for visually impaired users have not been systematically implemented or evaluated, leading to a lack of knowledge about their feasibility and usability. In this thesis, we designed and implemented three tabletop TUIs: although not all features had been fully developed, these interfaces were functional enough to be considered as proof-of-concept prototypes. In addition, we conducted several user studies, as shown in Table 6.1. We believe that the results and observations that we reported, whether qualitative or quantitative, constitute valuable resources on which people willing to develop TUIs for visually impaired users could base their future work. Although the Tangible Box prototype has not yet been evaluated, we hope that observations on how visually impaired students interact with it will be made during the following school year.

Table 6.1. Summary of user studies conducted for each interface. VI stands for Visually Impaired and BF for blindfolded.

Interface	Type	Goal	Participants
Tangible Reels	User study	Usability of the objects	4 VI users
	User study	Usability of the system	8 VI users
	Workshop	Pedagogical	3 VI and 2 teachers
Tangible Box	Interview	Designing applications	1 teacher
	Brainstorming	Designing applications	4 teachers
BotMap	User study	Usability of the interfaces	10 BF users
	User study	Usability and comprehension	8 VI users
	Design session	Realistic scenario + feedback	3 BF + 3 VI users

These studies enabled us to demonstrate the usability of the Tangible Reels as well as the usability of the proposed interaction techniques and feedback for the reconstruction of the tangible maps and diagrams. The educational workshop also enabled us to provide an initial investigation on the use of tabletop TUIs in the context of learning. A more detailed account and discussion of the results can be found in Chapter 3, 8. One major contribution of this thesis concerns the impact of panning and zooming on visually impaired people's mental representations. The results of the study that we conducted with BotMap are detailed thoroughly and discussed in Chapter 5, 5.4; in a nutshell, and very importantly, they showed that most visually impaired participants were able to pan and zoom using the two interfaces, and that most of them were also able to build a correct mental representation of "pan & zoom" maps, regardless of their age and age at onset of blindness. These results are in line with the amodal theory of spatial representation [174]. Despite the fact that the task was found to be cognitively demanding, these results open various avenues for the accessibility of complex representations, proving that when necessary, non-visual "pan & zoom" UIs can be used. In addition, the last study that we conducted suggested that navigational aids could help reduce cognitive load by reducing the number of operations required and help users to visualize the viewport's position on the map.

2 GOING BEYOND THE SCOPE OF THE THESIS

2.1 BLIND, LOW-VISION AND SIGHTED USERS

In the very beginning of this thesis, we stated the following: “Even though the interaction techniques and prototypes that we proposed were specifically designed for blind people, i.e. they did not rely on visual feedback, we use the term ‘visually impaired users’ to emphasize the fact that our work could benefit people affected by blindness as well as people having low-vision”. Designing interfaces for blind users restricts their design space, and raises several challenges or issues that are interesting to address, both from a theoretical and practical perspective. The three tabletop TUIs that we designed can be used by legally blind users, as they do not rely on any visual feedback. Although further developments are required to make them fully functional, we think that they could be independently used by blind users, without requiring the presence of a sighted person.

However, the use of visual feedback could be highly beneficial for low-vision users and could overcome the limitations imposed by the use of audio feedback only. For example, to reposition a tangible object in its right place, it could be possible to display a very bright stimulus in addition to (or instead of) audio feedback, which would certainly reduce the time required to find the correct position. Similarly, a visual cue could be displayed around an object that the user wants to locate, in addition to audio feedback. We chose to focus on non-visual feedback because it seems easier to augment audio-based interaction techniques with visual feedback than to adapt visual interaction techniques into purely audio-based ones. However, interfaces should be adapted to various types of users, for example by enabling them to choose between audio and/or visual feedback. In all cases, the tactile feedback provided by the tangible objects can be beneficial for both blind and low-vision users: therefore, research on the design of TUIs for blind users could feed research on the design of TUIs for low-vision users, and vice-versa. Another advantage of taking into account visual feedback, even though the interface is initially intended for blind users, is that it can facilitate collaboration between blind and low-vision users, but also between visually impaired and sighted users. The use of tangible objects to enhance interactive surfaces seems particularly interesting for low-vision users as it could facilitate interaction by providing increased haptic feedback. Interestingly, a project was recently launched to investigate the use of tangible interaction and augmented reality as a means to enable collaborative learning of spatial concepts between low-vision and sighted students (VISTE project[76]).

More generally, we believe that research on tabletop tangible maps and diagrams for visually impaired users could also benefit research on TUIs for sighted users. For example, Wolf and Bennett introduced the notion of Feelable User Interfaces (FUIs) [13], a subset of TUIs where the interface and its components, including feedback, “are not represented visually at all and therefore cannot be seen”. On the basis that TUIs commonly rely on visual representations (despite the fact that they were initially introduced to use physical rather than graphical objects, and even when physicality is the aspect being investigated), the authors deplore the dominance of the visual representation “to a detriment in the quality of the physical interaction” [13]. They

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[76] http://visteproject.eu/

suggested that the field of TUIs could benefit from specifically investigating the physicality of TUIs, and in particular a number of aspects that are inherently embodied into tangible objects and interaction, such as weight, friction, gravity, sounds resulting from the movement of an object over a textured surface and movement characteristics (speed, direction, collision, etc.). According to the authors, investigating the design of FUIs will enable us to gain a more thorough understanding of in-body perceptions (when moving an object above a surface), to take more advantage of haptic perception and to expand the design space of TUIs.

Also, in situations where the input and output spaces are not entirely unified, for example in multi-display environments composed of a tabletop TUI and several screens, users may be required to manipulate the tangible objects while looking at a different screen. In these cases, being able to track and reposition the objects without seeing them can be beneficial. Finally, in collaborative contexts, the use of audio feedback instead of visual feedback or perception could be considered as a way to ensure a certain level of awareness without disrupting the user's visual activity (see [93] for example). In particular, interfaces that support remote collaboration could benefit from conveying information about users' deictic gestures or about interaction between users with audio feedback, while restricting the use of visual feedback to only display the representation.

2.2 MAPS, DIAGRAMS AND OTHER FIELDS OF APPLICATIONS

The literature review that we proposed in Chapter 2 covered both maps and diagrams, unlike most research projects that very often focus either on maps or on diagrams. The main reason we chose to cover these two types of graphical representations is that they are based on the same *graphical primitives* (points, lines and areas), a definition of which we gave at the very beginning of Chapter 2. Therefore, findings concerning the legibility of these *primitives* with a particular display can apply to any graphical representations. For example, we mentioned a few articles that aimed to investigate how simple geometrical drawings displayed on a tablet can be recognized by visually impaired users, based on audio feedback and vibrations (e.g. [79]). These results could be used to improve the design of both digital maps and diagrams. Similarly, the Tangible Reels can be used to make digital points and lines tangible: as such, they are as relevant for maps as they are for diagrams (Chapter 3, 8.3). Also, the idea underlying the design of the Tangible Box can be applied to various types of tactile graphics, including maps, flow charts, bar charts, etc. As for BotMap, although it was specifically designed to make dynamic maps accessible to visually impaired users, other fields of applications could be considered, such as scatter plots (e.g. [256]).

We also observed that, although these two fields of application are commonly dissociated from one another, similar approaches have been investigated in terms of technologies. In that sense, the classification that we initially proposed for interactive maps for visually impaired users appeared to be relevant for interactive diagrams as well, hence our choice to extend it (Chapter 2, Part C, 2.2). In fact, the limitations and advantages of each approach, notably in terms of exploration, are very likely to be the same whether the display has been designed to display maps or diagrams. Therefore, when considering the design of a new interface to make a particular type of graphical representation accessible to visually impaired users, considering existing projects based on similar technologies may be useful, regardless of the nature of the graphical representations that they were intended to support. In particular, we observed that a number of techniques have been proposed to compensate for the inherent limitations of the approaches, such as using a grid to provide a frame of reference (e.g. [6]) or enabling the users to get an overview of a map or a diagram using verbal descriptions and/or sonification techniques (e.g. [193]). Although these aids may have been initially designed for one specific type of graphic, they could certainly be adapted for other graphics.

However, as pointed out by O'Modhrain et al. [219], considering both maps and diagrams may lead to an "engineering trap", where "design is driven by engineering principles or the technology itself, rather than being motivated by solid theoretical knowledge of the relevant perceptual and cognitive factors associated with use of the display and the tasks it is meant to support". These authors also warn of the "appealing but misguided idea that one type of display technology can be used for all kinds of […] graphics" [219]. For example, some technologies are more appropriate to convey complex representations (e.g. interactive tactile maps and diagrams), while others are more appropriate to convey updatable representations (e.g. force feedback devices). However, these characteristics (e.g. complexity and updatability) are not inherent to the nature of the graphical representations, but rather depend on the task that needs to be supported. For example, maps are not inherently more complex than diagrams: line graphs composed of several series are certainly more complex than maps composed of a limited number of landmarks only. Similarly, diagrams do not always need to be more updatable than maps: if the exploration of the map requires panning or zooming, or if a student is asked to reconstruct a map, then the map also needs to be updatable. At the same time, the specificity of a particular type of graphical representation must be acknowledged, and certainly requires different interaction techniques.

This thesis is the first formal investigation of tabletop tangible maps and diagrams for visually impaired users. Instead of focusing on one particular graphical representation, we chose to reflect upon design considerations and challenges and to propose solutions that could be easily adapted to different types of graphics. By doing so, we aimed to demonstrate the potential of TUIs for visually impaired users, to investigate and better understand to what extent their updatability could be beneficial, and to encourage their development. We acknowledge that additional interaction techniques and feedback would be beneficial when designing TUIs for a specific domain. For example, we illustrated in Figure 3.23 how a metallic bar could be fixed upon the table to provide a stable frame of reference onto which the Tangible Reels could easily be attached for timelines and bar charts. Inversely, in Chapter 5, we focused on one type of graphical representation ("pan & zoom" maps) but we discussed how the idea of using actuated tangible objects to increase the complexity and updatability of the representation could be applied to different domains.

Finally, although this thesis specifically relates to the accessibility of maps and diagrams, we believe that our findings could also be of interest for tables or more textual representations (e.g. formulas). In fact, during the brainstorming session organized as part of the Tangible Box project, some teachers proposed using the prototype to help students learn how to read tables or how to use conversion tables (see Appendix B). Given the fact that tables are accessed with screen readers, which usually read the tables row by row, it might be interesting to provide users with a way to mark up some cells with a tangible object or to quickly locate and read specific values (e.g.

by using actuated tangible objects that could move to the said cell). In addition, a set of interaction techniques based on tangible tools could be designed in order to provide users with basic functionalities to interact with tables. For example, Taher et al. [293] investigated how users could interact with a 10 x 10 motorized bar chart to perform the following tasks: annotation, navigation, filtering, comparison, organization and sorting. A similar study could therefore be envisaged for tangible tables.

More generally, we believe that the solutions that we proposed could inform the design of non-spatial TUIs for visually impaired users, including programming, storytelling, games, etc. Although these domains have barely been considered for visually impaired users (although, see [221] for an example of a tangible musical application and [300] for an example of a physical programming language), they might be studied more and more as TUIs become more common and easy to develop. When designing such interfaces, researchers or developers will certainly encounter the same design challenges as the ones we came across: how to ensure stability, how to increase the expressiveness of the tangible representation, how to provide suitable feedback, etc. Design challenges specific to the domain will certainly need to be considered as well, but building on solutions that have already been designed and evaluated, and that proved usable, may facilitate the design process. For this reason as well, the design framework that we proposed for the Tangible Box project might be a good starting point for the design of non-visual and non-spatial TUIs, notably concerning the type of tasks that can be supported or particularly adapted to tabletop TUIs.

3 RELATION WITH OTHER FIELDS OF RESEARCH

3.1 EMBODIED COGNITION

As we briefly discussed in Chapter 2, Part D, 2.4.2, advances in the field of *Embodied Cognition* highlight the importance of movement in knowledge acquisition and memorization, and, therefore, the possible benefits of physical (active) manipulation of reconfigurable representations over (passive) exploration of static ones. Although we did not address this question, we gathered feedback that echo such findings: with the Tangible Reels most participants indicated that the reconstruction phase helped them to understand the maps, and the teachers, during the educational workshop, posited that the reconstruction was beneficial in terms of learning, as it certainly helped children memorize the position of the tangible objects and, therefore, the location of the city that was represented. Similarly, during the brainstorming we organized for the Tangible Box, teachers said that the actions of moving one object along a path, following guidance instructions and moving one object from one place to another were certainly beneficial in terms of learning, notably thanks to the kinesthetic feedback provided by the manipulation of the tangible objects. Finally, some participants who took part in the user study of BotMap indicated that moving the sliders helped them to better visualize in which direction they were moving the viewport.

Based on these observations, two questions would be worthy of further consideration, notably by conducting additional user studies and building on existing literature: 1) Does reconstruction affect spatial memory? 2) Does manipulating tangible representations facilitate the acquisition and learning of new concepts, compared to static graphical (or verbal) representations? The second question is subject to an ongoing debate about the real benefits of TUIs for learning, and we refer the reader to [188,189,218] for more detailed discussions on this topic. As for the first question, it is closely related to a number of studies that investigated the impact of gestures on spatial memory. For example, Tan et al. [296] asked 28 participants to memorize the position of a set of items by dragging them into a grid, either using a touchscreen or a mouse. Performances (measured in terms of distance errors) were better in the touch condition. The authors concluded that "kinesthetic cues aid spatial memory". Similarly, Jetter et al. [124] asked 20 participants to relocate items on a grid that they had previously explored through panning, either with a mouse or by touch. Performances were again better for the touch condition[77]. Therefore, it might be hypothesized that both proprioceptive and kinesthetic feedback provided when reconstructing a map or a diagram could facilitate the encoding of locations in spatial memory. However, one difference in these two studies was that users had to explore a digital canvas, not place objects on the canvas (therefore there was no physical manipulation/reconstruction); in addition, the cognitive workload induced by audio guidance instructions might take over the benefits of kinesthetic and proprioceptive feedback.

Very recently, Giraud et al. [78] conducted a study with 24 visually impaired children to assess the benefits of an interactive small-scale model over a raised-line map. The model was composed of a wooden tactile map of Paris, with various textures and landmarks that were interactive (i.e. when the user touched a landmark, audio descriptions were provided). In addition, a set of interactive wooden pieces representing ramparts that have been built over time could be placed on top of the map (as in a jigsaw puzzle), therefore allowing users to switch between different periods of time by physically manipulating the different pieces of the model. This model was compared to two raised-line maps and a Braille booklet presenting the same content as the model. Children could explore the model or the maps for 35 minutes, and then had to answer a number of questions. The results showed that the interactive model resulted in better performances in terms of space and text memorization. However, this improved performance could be due either to the ability to physically manipulate the objects (compared to the raised-line maps that were static), or to the use of audio descriptions (compared to the Braille booklet, which probably required participants to spend more time reading the descriptions, and may therefore have allowed them less time to memorize the pieces of information, which were "quite long and difficult to memorize"). In fact, the authors stated that the benefits of the model over the raised-line map did "not rely on a better memorization of landmarks, but rather on a better comprehension of the text".

Except for this study, we are not aware of any study that specifically investigated the benefits of active reconstruction over passive exploration by visually impaired users and so these benefits still need to be supported by empirical results.

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[77] However, when panning and zooming was necessary, performances did not increase.

3.2 CONSTRUCTIVE ASSEMBLIES

Constructive assemblies were first identified by Ullmer and Ishii [305] as a subset of TUIs, and can be defined as TUIs "that involve the interconnection of modular physical, interactive *units* to formulate larger constructions that are automatically or manually put-together" [162]. The interfaces can support 3D (e.g. Topobo [246]) or 2D constructions (e.g. Gaussbricks [167]) and have been largely used for hands-on education, notably because "they provide 'enjoyment', and are 'more motivating [and] more engaging" [162]. Recently, Leong et al. [162] provided a conceptual framework that aimed to "facilitate systematic investigation and critical consideration of constructive assemblies" (Figure 6.1). In particular, they identified four themes that characterize the user experience: efficiency vs exploration (to what extent the system encourages the user to try out different configurations); repulsion vs attachment (to what extent the users "either dispose or keep the modules"), constrained vs expressive (how expressive the construction is); novice vs experts. By adjusting several parameters related to these themes (e.g. number of connections, aesthetics, etc.), designers can influence users' experience and better meet their needs.

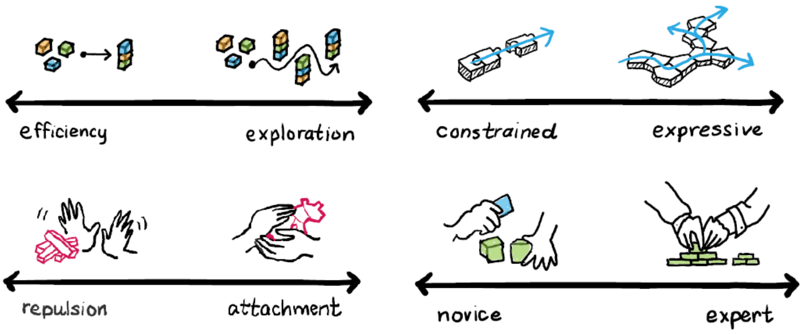

Figure 6.1. Four design themes for constructive assemblies [162]**.**

The Tangible Reels interface was initially designed to support the reconstruction of graphical representations: as such, it can be seen as a constructive assembly system, which barely supports free exploration (the user must follow the instructions). However, we also discussed how the system could be used to support the unguided construction of graphical representations, the properties of which could be described with audio feedback as the student is manipulating the Tangible Reels. For example, if geometric shapes were being constructed, their name, area and perimeter could be given; if a line graph was being constructed, indications about the line slope could be provided (negative vs positive). Building on the framework proposed by Leong et al. [162], another version of the Tangible Reels could be developed to better support such tasks. In particular, the system could support a higher degree of exploration; the Tangible Reels could be redesigned or enhanced with interactive features in order to be more attractive and engage the students more; the number of Tangible Reels could be increased and their size decreased to allow for a greater expressiveness. These possible improvements are shown in Figure 6.2, which is based on figures presented in [162], where existing systems were analyzed along the four design themes:

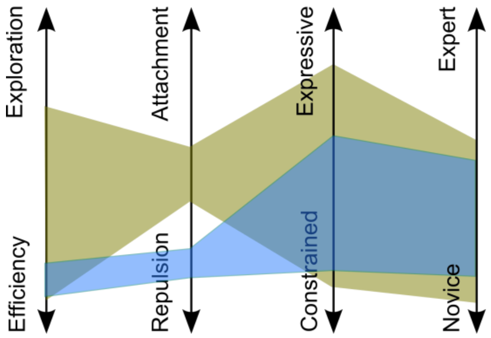

Figure 6.2. The Tangible Reels interface analyzed with the framework proposed in [162]**. As in the article, "blue marks the current system's qualities; green indicates a direction for future iterations of the respective systems".**

3.3 TOKEN+CONSTRAINT

Besides interactives surfaces and constructive assemblies, Ullmer et al. proposed another approach for TUIs, called "token+constraint", and characterized by the use of two types of tangible objects [308]: on the one hand, tokens represent (aggregates of) digital information (although the term is the same as the one used by Holmquist et al. [102], there is a slight difference in that in [308] tokens mostly contain data and therefore act as "containers" rather than "tokens"); on the other hand, constraints "are confining regions that are mapped to digital operations" and limit how the tokens, when placed inside, can be manipulated. These constraints are often mechanical (e.g. a rack onto which tokens can be placed and manipulated) but can also be visual. Examples of digital operations associated with constraints include dynamic binding, manipulation of a continuous parameter, playback of digital media and storage and retrieval of a digital state. Token+constraint systems usually have two phases [308]: first, users must place the token within the constraint (*associate* phase); secondly, they can manipulate the token, whose movement is constrained (*manipulation* phase). Figure 6.3 shows basic and more complex examples of token+constraint modules:

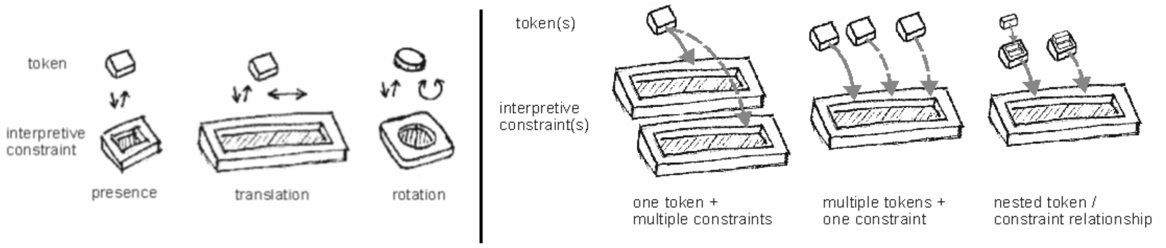

Figure 6.3. Simple (left) and more complex (right) token+constraint relationships. Retrieved from [308]**.**

We believe that the Tangible Box prototype could be an interesting platform to begin investigating the use of token+constraint interfaces for visually impaired users. Although there are no specific reasons why these types of interface would be more challenging to design for visually impaired users than for sighted users, we think that the usability of TUIs for visually impaired users may be enhanced by using mechanical constraints instead of standard input devices (e.g. keyboard) and/or audio feedback. In fact, the tangible menus that we proposed in

Chapter 4, 4.2.4 (e.g. Figure 4.5) can be considered as token+constraint modules, although they differ in three main ways: 1) because the tangible objects cannot be lifted off the surface, the *associate* phase cannot consist in placing (and then removing) the token in the constraint, but rather in moving it inside/outside (although the difference is subtle, it may result in the token+constraint module being less intuitive, and also prevent the design of nested token+constraint relationships); 2) for the *manipulation* phase, rotation cannot, up to now, be considered (due to the properties of magnets, rotating the upper part of the tangible object does not result in the lower part of the object being rotated); 3) the constraints we proposed are composed of lines that have been printed in relief: they are therefore half way between mechanical and graphical/tactile constraints. This last specificity offers a number of interesting possibilities for the design of token+constraint interfaces.

The first possibility would be to vary how restrictive constraints could be, by using lines of different thickness or with different patterns, or by using several lines instead of one, as illustrated in Figure 6.4. In addition, one could consider printing the representation using thermoforming techniques: in that case, it would also be possible to vary the height of the lines (the higher the line, the more restrictive the constraint). It might even be possible to use magnetic elements as constraints, which would attract or repel the tangible objects–although such a feature should be carefully designed, as the lower part of the object should not connect to the magnetic constraint when the tangible object is inside. Another idea would be to print "notches" that would indicate to the users where the tangible objects must be placed (e.g. for the Timeline application, where objects representing historic figures must be placed within the corresponding period).

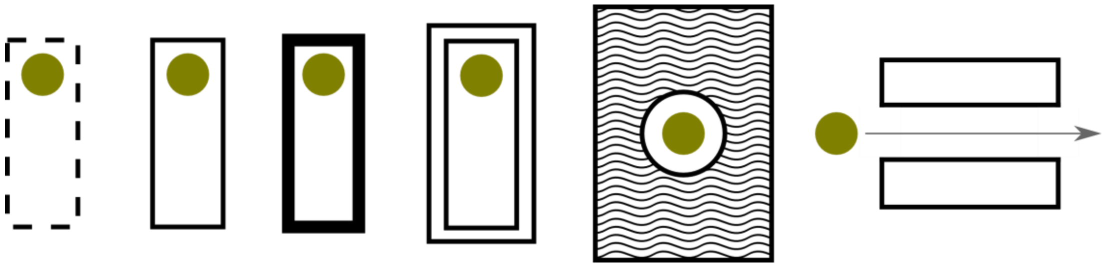

Figure 6.4. Possible raised-line token+constraint modules for the Tangible Box. Constraints are in black, tokens in green. The last two pictures illustrate how users could be guided to place tokens on a notch (void area inside a filled area) or to move them through a tactile "frame", for dynamic binding.

In terms of digital operation, one interesting aspect to consider is the use of token+constraint for dynamic binding. Because the Tangible Box can only track the lower part of the objects, it cannot detect which hats have been clipped on a specific object, which raises an issue when the system needs to assign to each ID a specific piece of information (e.g. when "Paris" must be assigned to the tangible object representing the Eiffel Tower, the system has no way of knowing which object represents the Eiffel Tower). Although the system may infer which tangible object represents a specific piece of information (as in the Talking Clock application, where the system infers which objects represent the extremity of the minute hand, the center of the clock or one menu selection), there are some cases where it would be interesting to provide users with a way to dynamically bind one specific tangible object with one piece of information. One tactile frame/bridge could be used for that purpose, as illustrated in Figure 6.4, right: the user would need to scan the token by moving it through a frame. Using such a module, the system could ask the users to "scan" one object and assign to it the corresponding piece of information; on the other hand, for expressive activities, the user could place an object in this frame whenever they want to assign to it a new piece of information (which could be recorded using a microphone).

Finally, Ullmer et al. [308] stated that one characteristic (and limitation) of token+constraint approaches is that "for application requiring spatial content with geometrical content, [they] do not support the continuous two-dimensional positioning common to graphical interfaces and interactive surface TUIs". However, we believe that the token+constraint approach could also be considered when designing tangible maps and diagrams with the Tangible Box, not only for tangible menus or "binding frames", but also for spatial content. For example, the boundaries of a country, printed in relief, could serve as a mechanical constraint which would delineate where the user can place the objects representing the cities of the said country.

3.4 SWARM USER INTERFACES

As we already discussed in Chapter 2, Part D, 4.1, our work taps into the emergent field of Swarm User Interfaces, which are « human-computer interfaces made of independent self-propelled elements that move collectively and react to user input » [81]. SUIs are inspired by the Ishii's vision of Programmable Matter [112]; they suggest that in a couple of years or decades, fully physical and reconfigurable interfaces may exist, composed of a large number of elements such as robots (see [53,54] for examples of swarm robotics) or drones [260]. While technological advances are necessary to reach such a high degree of physicality and reconfigurability, we believe that BotMap is strongly correlated with these new types of interfaces, although it is composed of a very limited number of "self-propelled elements", and requires the use of an external camera to react to user input (whereas, according to Le Goc and al. [81], the ability of the elements to directly react to user input is a necessary condition for a display to be considered a SUI).

SUIs can be used for a number of applications, as illustrated in [81]. With BotMap we further illustrated the potential of such interfaces to physically display "pan & zoom" maps, a domain that has not yet been investigated by SUIs, or by actuated tabletop TUIs. In addition, we also demonstrated that SUIs could not only benefit sighted users, but also, and even more relevantly, visually impaired users. In fact, BotMap is the first prototype that uses several robots on top of an interactive table to make graphical representations accessible to visually impaired users; as such, it can be considered as the first non-visual SUI, even though very "coarse-grained" [81].

The development of SUIs for the visually impaired could benefit from existing research on SUIs for sighted users, and notably from the work of Le Goc et al. [81], who, to our knowledge, were the first to formally define what a SUI is, and to formally investigate their design principles and challenges. Figure 6.5 (left) illustrates the design space of SUIs that they proposed, organized around three themes: display, interaction and environment. Figure 6.5 (right) shows, in green, the different parts of this design space that we explored though the development of BotMap. Drawing upon this design space, we briefly discuss four aspects of SUIs that we find particularly interesting (and challenging) for visually impaired users, and illustrate them by discussing how they could enhance BotMap (Figure 6.5, right, in orange).

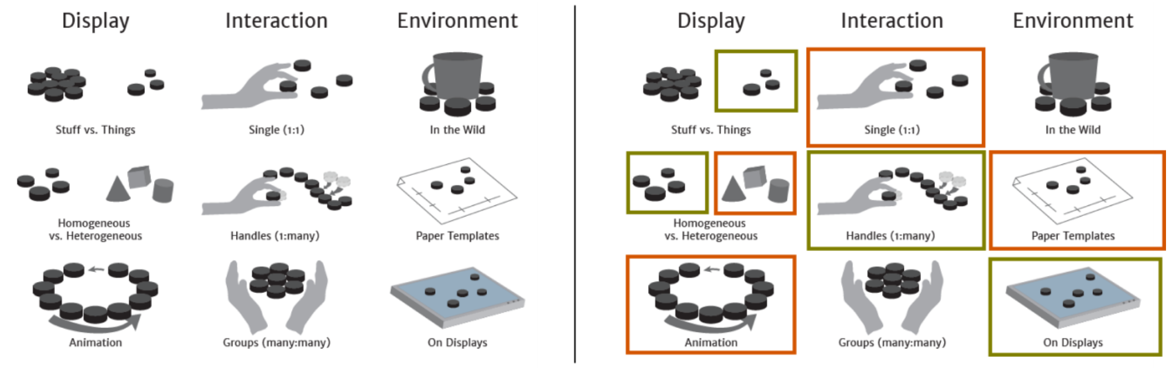

Figure 6.5. Left: design space of Swarm User Interfaces, and particularly of Zooids [81]**. Right: in green, the aspects that we explored with BotMap; in orange, the aspects that would be worth considering to enhance BotMap. (Retrieved from / after** [81]**.)**

Display: Homogeneous vs heterogeneous. SUI elements can be homogeneous or heterogeneous, in which case they are not interchangeable. Although using heterogeneous elements can be an advantage, notably in terms of *affordance*, it can also reduce the responsiveness of the interface, as elements cannot be swapped to optimize their displacement. Regarding BotMap, several users appreciated the fact that all robots were similar and indicated that having to touch each object to distinguish its shape would be a tedious process; however, two envisaged using different shapes to convey more information about the landmark being explored (e.g. pyramids in Egypt). Therefore, if heterogeneous elements are used, designers should consider how to make them very readily identifiable by touch (and/or sounds) and ensure that this aspect does not disturb exploration. Having said that, using heterogeneous objects may be very useful for low-vision users.

Display: Animation. When they are not used, SUI elements cannot simply disappear and need to be placed somewhere, which "force[s] designers to think about how to animate appearance and disappearance". With BotMap, robots move to parking spaces located on each side of the viewport. All users reported that the noise emitted by the robots when moving helped them to get a sense of the state of the system, and some mentioned that it helped them to know how many landmarks were displayed, and where. However, robots were not assigned a fixed landmark, so the displacement (and sound) of the robots was not correlated to the displacement of the viewport. Additional work may investigate how to help users understand the new viewport's position by relying on audio animation and, for low-vision users, whether having robots moving in all directions (instead of in the opposite direction of the viewport) could negatively impact their mental representations.

Interaction: **Single**. SUI elements can be controlled individually, or collectively, and therefore support a large range of interaction techniques. With BotMap, only the sliders used for panning and zooming could be manipulated by the users. However, during the third user study that we conducted several participants indicated that they would like to be able to directly interact with one robot, for example to get more details about it, but also to be able to retrieve pieces of information concerning surrounding landmarks. Such an aspect is worth investigating particularly for visually impaired users as it could limit the use of voice commands, which can be difficult to memorize, and the use of dedicated input devices (e.g. keyboard), which can disrupt the exploration process.

Environment: Paper templates. SUIs can be used on regular graphical displays, but they can also be used on paper "that contains all the necessary annotations, provided these are stable over time". There are two situations where using paper over regular graphical displays might be particularly relevant for visually impaired users: firstly, if the device is intended to be used only by blind users, visual feedback is not necessary; secondly, if the robots can move over a tactile surface, then the expressivity of the system can be considerably enhanced (which is the approach we considered with the Tangible Box). However, in that case, the prototype would no longer support panning and zooming. One scenario that could be envisaged and that would still be related to maps would be to use BotMap for flow maps: the map could be printed on a tactile support, and the movement of the robots would represent the movement of information or objects.

To sum up, there is still a large number of avenues to explore with SUIs, regarding their design space, the audience they are designed for (sighted vs visually impaired users) and the domains for which they can be particularly relevant. In particular, SUIs "provide a promising platform to physicalize many traditional 2D information visualizations" [81] and can therefore be considered as an interesting way of implementing Data Physicalizations.

3.5 DATA PHYSICALIZATION

The term data physicalization refers to both "a physical artifact whose geometry or material properties encode data" [121], and an emergent research field that "examines how computer-supported, physical representations of data (i.e., physicalizations), can support cognition, communication, learning, problem solving and decision making" [121]. Data physicalizations can be static or dynamic, in which case they support animation (the physicalization is reconfigured by the system itself) and interaction "either via sensing and actuation (synthetic interaction) or through purely physical manipulation (physical interaction)" [121]. In that sense, we think that the three interfaces we developed are strongly related to this emergent field of research, although there is a difference between TUIs and physicalizations: "TUI[s] mostly focuses on information *input* and *manipulation* tasks (with output being used to assist in the task) while [Data Physicalization] mostly focuses on information *output* and *exploration* tasks (with input being used to assist in the task)" [121].

According to these definitions we believe that BotMap can be considered as one dynamic data physicalization for visually impaired users: the aim was clearly to provide a way to *explore* large geographical maps, and the interaction techniques for panning and zooming assisted them in the task. In fact, the implementation of a system and of interaction techniques supporting view transformations such as pan and zoom was mentioned in the research agenda for data physicalization proposed by Jansen et al [121], and although our system was designed for visually impaired users, it may contribute to future physicalizations for the exploration of "pan & zoom" maps by sighted users. On the continuum between TUIs and data physicalization, the Tangible Box is probably situated somewhere between the two: although it supports *manipulation* tasks, it can also simply be used to *explore* graphical representations. As for the Tangible Reels, we believe that in its first version, since we had not designed interaction techniques that enabled users to manipulate and edit the tangible representation, is was more a low-resolution physicalization than a TUI (the construction did involve manipulation, but the final objective was for the users to *explore* the map); in its second version, we implemented two additional features (construction and annotation), therefore taking it towards the "TUI" end of the continuum. The potential of physicalizations for visually impaired users was clearly identified by Jansen et al., who suggested that "with physicalizations, visually-impaired data analysts may be able to explore data through the geometry and material properties of data artifacts in more ways than possible with currently established techniques" [121]. We fully agree with this remark, and hope that the three interfaces that we developed, although they were not all designed to specifically support exploration, will serve as a starting point for the design of data physicalizations for visually impaired users.

In addition to the question of accessibility, Jansen et al. [121] identified four main benefits of physicalizations: they leverage our perceptual exploration skills; they provide cognitive benefits; they bring data into the real world; they engage people. We believe that these (potential) benefits are also, and particularly, relevant for visually impaired users. However, be it for sighted or visually impaired users, further research is needed to gain a more comprehensive overview of which aspects of physicalizations are correlated with particular benefits. For example, there is a need to better understand how efficient particular physical variables (e.g. smoothness, height, weight, etc.) can be to convey certain types of data, but also to conduct empirical studies to evaluate animation and interaction techniques that could help users efficiently explore data physicalizations (e.g. [293] evaluated interaction techniques for physically dynamic bar charts and [120] compared the use of physical 3D bar charts to onscreen 3D bar charts).

We believe that research on physicalizations for sighted users could greatly benefit from the existing work on tactile graphics for visually impaired users, notably concerning the way two-handed exploration can be beneficial, the importance of providing a stable frame of reference and the properties of physical variables (e.g. see the grammar of physical variables proposed by Vasconcelos et al. [318]). Conversely, research on the development of maps and diagrams for visually impaired users should also consider recent advances on physicalizations for sighted users, notably in terms of implementation, interaction, animation and evaluation.

3.6 GOING BACK TO THE BIGGER PICTURE

All in all, this thesis tapped into a various range of research areas, which share a common goal: taking better advantage of our inherent ability to manipulate and interact with physical objects, or, in other words, to "leverage our perceptual abilities" [121]. In particular, when these perceptual abilities do not include visual perception such approaches make perfect sense and should be more fully considered to improve traditional methods that are, by nature, physical (e.g. raised-line graphics and corkboard-based graphics). More precisely, the three interfaces were somewhat related to the emergent field of data physicalizations and could be improved by building on theoretical and empirical works concerning this field. In addition, we discussed to what extent the Tangible Reels are related to constructive assemblies, the Tangible Box to token+constraint interfaces and BotMap to Swarm User Interfaces.

The first figure of this thesis (Figure 1.1) depicted interaction paradigms that have largely been explored to give visually impaired and sighted people access to graphical representations: throughout this thesis, we investigated approaches that have so far received very little interest from researchers working on possibilities for visually impaired users. Figure 6.6 is an updated version of this first figure, showing the approaches that we investigated (in italics and bold). In addition, we believe that there are three ideas that we proposed and that could be as relevant for visually impaired as they are for sighted users: 1) making tangible representations more expressive by physicalizing not only punctual symbols, but also linear symbols (Tangible Reels); 2) enabling users to interact with tangible objects placed on top of a paper display (Tangible Box); 3) using small robots to display physical and yet dynamic "pan & zoom" maps.

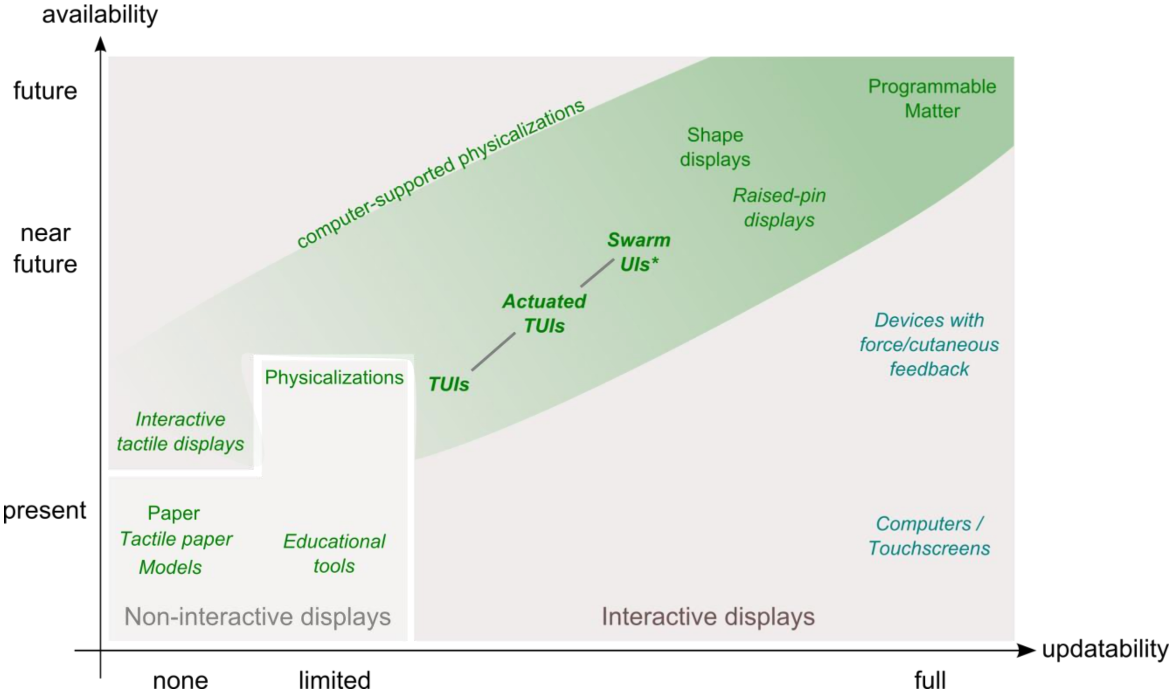

Figure 6.6. Updated version of the figure used in the introduction. In bold and italics, approaches that we investigated in this thesis to make maps and diagrams accessible to visually impaired users.

4 PERSPECTIVES

4.1 IMPROVING AND COMBINING THE THREE INTERFACES

4.1.1 SUMMARY OF PROPOSED PERSPECTIVES

At the end of the three previous chapters, we listed a number of ways to improve the interfaces that we developed. In particular, for the Tangible Reels, we discussed different ways in which the design of the tangible objects could be improved, be it by reducing their size, equipping them with double retractable reels, making them actuated or enabling the construction of curves (Chapter 3, 8). We also suggested implementing additional functionalities that would enable users to edit the map, notably to display or hide points of interest. Concerning the Tangible Box, the main developments concerned the implementation and evaluation of applications, the use of a smartphone (to track the user's fingers and the tangible objects, to enable users to log into the application and to enhance the applications with touchscreen menus), and the development of tangible menus (Chapter 4, 6). As for BotMap, we mainly proposed to evaluate the benefits of a tangible viewport and to design additional interaction techniques that would allow users to directly interact with the robots (Chapter 5, 7).

We also acknowledge the need to conduct additional user studies with the three interfaces. Concerning the Tangible Reels, such studies could specifically investigate whether the active (re)construction of a map or a diagram can have a positive impact on the acquisition of spatial knowledge. At the time of writing, applications for the Tangible Box were still under development, making it impossible to conduct evaluations that would be necessary to assess the usability of the prototype (and notably whether to adjust the strength of the magnet, the position of the keyboard, the shape of the tangible objects, etc.), but also to better understand to what extent trial and error activities, for example, could help students reinforce or discover concepts. Another interesting evaluation would consist in comparing whether following a path (e.g. blood flow) with an object can lead to better memorization, compared to performing double taps on different elements placed along the same path. Another perspective could be to observe how the Tangible Box can impact the way teachers organize their lessons and develop their own curricula.

4.1.2 SHORTER AUDIO FEEDBACK

The three interfaces use audio feedback (excluding the inherent tactile feedback provided by the tangible objects), and more precisely Text-To-Speech (TTS). However, the transient nature of verbal feedback can be an issue. For example, in BotMap, the given feedback was not always consistent with the actual position of the sliders. With the Tangible Reels, this could also result in the objects being misplaced (by the time the system indicated that one object had been correctly placed, users may have already moved the object to an incorrect position).

It would therefore be interesting to use shorter feedback, such as auditory icons ("brief sounds that represent objects, functions, and actions" [47] or, in other words, "caricatures of naturally occurring sounds" [75]), earcons ("abstract, synthetic and mostly musical tones or sound patterns that can be used in structured combinations" [47]) or spearcons ("spoken phrases sped up until they may no longer be recognized as speech" [47]). Dingler et al. [47] introduced two additional types of short audio feedback: earcon-icon hybrids (composed of the opening sound of an earcon followed by an auditory icon) and sized hybrids (e.g. "the sound representing huge objects is low pitched and long for example, whereas a short and high pitched two note melody is used for small features"). Using these different types of short audio feedback, a large palette of feedback could be created and be used, for example, to convey information about the status of the objects (e.g. whether they are detected or not), their identity (e.g. in BotMap a higher pitch could be used for cities than for villages) or the mode currently selected (e.g. exploration or construction).

4.1.3 AUDITORY AND HAPTIC LINES AND AREAS

Conveying information about lines and areas using a TUI is challenging. In this thesis, we designed the Tangible Reels to make lines tangible and proposed, with the Tangible Box, to use tangible objects on top of tactile graphics on which lines and areas can be printed. However, whether it is for BotMap of for the Tangible Reels, it would be interesting to allow users to explore non-physical lines and/or areas, therefore combining digital and hybrid approaches.

Once again, audio feedback could be considered, as we illustrated in Figure 3.22, left: whenever the user's finger is "inside" an area, appropriate feedback can be provided. For example, in SeaTouch [283], different sounds are played depending on the position of the force-feedback stylus (e.g. a looping water sound is played when the stylus is in contact with the sea and bird sounds are played when the stylus is in contact with the land). Such sounds could be played in the background, so as not to disturb the user. More simply, a musical note could be played whenever the user moves from one area (e.g. a country) to another.

Another type of feedback that has been investigated to help users understand when they are crossing a line and/or moving from one area to another is the use of vibrations. For example, in the prototype of Bardot et al. [6], users were equipped with a smartwatch that vibrated whenever they were moving from one state to another. Different patterns of vibrations could be envisaged (more, or less, strong, discrete vs continuous, etc.) to help users identify the nature of the area or lines. For example, in BotMap, different patterns could be used to help users distinguish between lines that represent boundaries and lines that represent rivers.

Finally, considering more advanced technologies, lines and areas could be conveyed through touch surfaces that provide (direct or indirect) cutaneous feedback. In her discussion about possible ways to enhance interactive tactile maps, Brock [23] reviewed a number of prototypes, including, for example, TeslaTouch [8], STIMTAC [2] or FingerFlux [335]. We refer the reader to her discussion for further details. Although these innovative interfaces are mainly confined to laboratories, the notable exception of the Ultrahaptics project is worth mentioning: originating from academic research [33], the project is now supported by a company[78] that provides hardware and software products for the development of applications, thanks to which users can "touch virtual objects in mid-air". The system is composed of an array of ultrasonic transducers that project ultrasounds onto the user's hand, and therefore create the impression of physically touching an object (Figure 6.7).

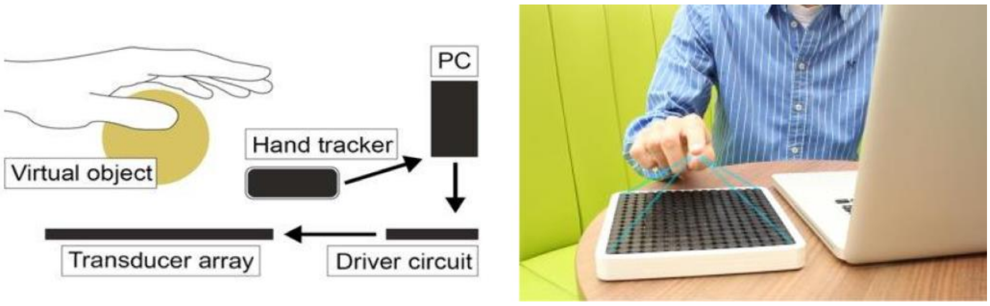

Figure 6.7. The Ultrahaptics system [33]. **It is composed by an array of ultrasonic transducers that project ultrasounds onto the user's hand.**

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[78] https://www.ultrahaptics.com/

4.1.4 COMBINING THE THREE INTERFACES

Although the three interfaces are relatively different from each other, there are different ways to "combine" them. Firstly, the Tangible Reels could be used with the Tangible Box by replacing the sucker pad with a magnet and designing mini-retractable reels. Secondly, to increase the expressiveness of the graphical reconstructions built with BotMap, the use of retractable reels with robots could be envisaged, although it raises a number of design and implementation challenges, notably to avoid collision between robots and the retractable reel strings, and to connect and disconnect the robots. A more feasible approach would be to equip certain robots with retractable reels and to let the users connect or disconnect the robots when necessary (two robots that need to be connected could vibrate or emit sounds to guide the user). In all cases, future work on Swarm User Interfaces will certainly open interesting avenues for interfaces composed of a (very) large number of (very) small robots, and if a sufficient number of robots are used, then the robots could relocate in order to display lines (as illustrated in [81] with an application for drawing Bézier curves). Another interesting perspective for BotMap, which we already discussed in 3.4, would be to use robots (optionally equipped with retractable reels) on top of a tactile graphic, similar to the Tangible Box.

4.2 COLLABORATIVE TUIS FOR VISUALLY IMPAIRED USERS

In Chapter 2, Part D and Chapter 2, Part E, 2, we reviewed a number of studies that showed the potential of TUIs for collaborative activities, and particularly for collaborative learning activities (e.g. [271]). We also discussed the fact that the development of such interfaces for visually impaired users might raise a number of challenges, notably in terms of feedback, which must be carefully designed to help users maintain a sense of *awareness*. Existing work mainly relies on digital prototypes, and notably on the use of a force-feedback device. For example, Reid and Plimmer [251] used a Phantom device to help blind students learn how to write and sign a document. As the teacher forms the shape of a letter on a tablet, the student experiences parallel feedback. McGookin and Brewster [191] developed an application where two blind participants could browse and modify the same graph using their own force-feedback device. Sallnäs et al. [264] presented a study with two haptic and visual prototypes that enabled sighted and visually impaired students to collaborate during the learning of geometrical concepts.

Some authors reflected upon the challenges raised by the design of collaborative non-visual interfaces (e.g. [147,152,342]). Among them, Kunz et al. [152] identified one major issue: while visual information allows sighted users to see "at one glance" the state of each element of the interface, this is usually not the case for blind users because the information is "serialized" when conveyed with audio or tactile feedback. Köhlmann [147] also identified four barriers to collaborative learning for visually impaired users: resolution (i.e. amount of information that the user can access simultaneously) and orientation, semantics (how the pieces of information are distributed over several media related to each other), synchronicity (i.e. difficulty in accessing the last updates), and social presence (i.e. difficulty in perceiving facial expressions and deictic gestures, for example).

More recently, Microsoft Research proposed an innovative tangible interface that enables several visually impaired children to collaborate in order to learn the basis of computer programming, based on Torino, a physical programming language [300]. Children can manipulate physical "instruction beads" (play, pause and loop), each of them representing a line of code in the program. A thorough analysis of twelve learning sessions conducted with five pairs of children (one pair of partially-sighted children, one pair of blind, one pair of sighted, and two pairs of mixed blind-sighted children) gives a number of interesting insights on the design of collaborative TUIs for visually impaired users, notably concerning "the role of touch, audio and visual representations" [300]. To our knowledge, this is the most advanced work on collaborative TUIs for visually impaired (and sighted) users. Given the high number of collaborative TUIs for sighted users that proved useful and usable, we believe that this field of research would be worth investigating further. The following sections briefly present two research projects that are currently being undertaken at our laboratory and that aim to contribute to this research area.

WORK IN PROGRESS: COLLABORATIVE LEARNING OF SPATIAL CONCEPTS

Following up on a talk that I gave at the EPFL (Lausanne, Switzerland), a collaboration was initiated between researchers and students from the EPFL (P. Dillenbourg, W. Johal, A. Ozgür) and Toulouse (C. Jouffrais, V. Tartas, A. Kolodziej and myself). In Chapter 2, Part D, 4.2.2, we described the robots developed by Ozgür et al. [223], called Cellulos. They provide haptic feedback, which can be used to guide the user towards a specific position, or to prevent them from going in a certain direction, for example. Their relevance for collaborative and educational activities has been demonstrated in various scenarios, such as for learning wind meteorology [224].

One goal of this project, conducted as part of Agnieszka Kolodziej's thesis, is to design an application that will take advantage of the benefits of the Cellulos to foster collaboration between visually impaired (and sighted) children and help them acquire knowledge about important spatial concepts (e.g. estimating or comparing distances and directions; understanding changes of scale; understanding tactile maps, etc.). Another goal of this project is to better understand how children's vocabulary evolves as they discover and learn spatial concepts. From a human-computer interaction perspective, another objective is to design and evaluate interaction techniques and feedback that support collaboration between sighted/visually impaired users.

Based on two brainstorming sessions, one of which included specialized teachers and tactile graphic specialists, different scenarios were identified and are currently being developed. The aim is to provide teachers and students with a number of activities of increasing difficulty that could be used at different stages of the learning process. They rely on plans, and more specifically on the classroom's and school's floor plans. At least one student always sits in front of the plan, which is printed on a large sheet of paper and on which 3D-printed elements are placed, which represent various elements (e.g. a table, a wall, etc.). The robots are placed on this paper and they represent one child who is in the classroom or the school: if the child moves, the corresponding robot moves accordingly. The scenarios can require (remote) collaboration between one student and one teacher, or several students, or several groups of students[79]. A brief description of these activities is given in Appendix E.

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[79] Although scenarios have been designed for one student only, we only describe scenarios that involve at least two users.

WORK IN PROGRESS: TANGIBLE GAMES

Games are another interesting field of application for collaborative TUIs, and several collaborative and tangible games have already been developed for sighted users (e.g. [3]). However, the literature on tangible games for visually impaired users is much more restricted. In fact, board games are rarely accessible for visually impaired people because, like maps and diagrams, they must be adapted using particular materials and techniques (e.g. by adding tactile cues on cards to help users identify them).

Based on the findings of this thesis, a project has been launched within the framework of the AccessiMap project, in collaboration with AccessiJeux[80], a French not-for-profit association which aims to improve the accessibility of board games for visually impaired users. The main objective of this project is to develop an accessible and tangible board game that could be used at the IJA. From a research perspective, such a game could serve as a platform to study how different feedback and interaction techniques could support and foster collaboration (and cooperation) between players, but also to investigate whether augmenting a traditional game with interactive features could enhance user experience.

The chosen game is called "Little Red Riding Hood"[81], and has the particularity to be not only a collaborative game, but also a cooperative game, meaning that the players must decide together which action to take in order to win the game. The game is composed of a game board with a path made of about thirty squares, a set of cards, a set of tokens and two pawns (one standing for Little Red Riding Hood, the other standing for the Wolf). The goal of the game is for Little Red Riding Hood to reach her grandmother's house before the Wolf. On every turn, the players have several options, which result in Little Red Riding Hood and/or the Wolf moving forward towards the grandmother's house, depending on the number of stones drawn on each token (the stones are only visible when the tokens are turned upwards).

In a very early version of the tangible game that we developed, we chose to replace the two pawns by two small robots (the ones we used for the BotMap prototype), which move forward whenever required. By doing so, we aimed to make the game more attractive. In fact, at the end of the educational workshop that we conducted with the Tangible Reels, the children were shown the Ozobots robots and they expressed a great interest in them. The physical cards were replaced by digital cards; users can pick up a new card or retrieve the name of a previous card by performing touch gestures (e.g. swipes) on the cards, which are bordered by a tactile frame. As for the physical tokens, we used a set of tangible tokens with a fiducial marker on one side. The number of stones on each token is read out by the TTS whenever a new fiducial marker is being detected (i.e. whenever a token is turned upwards by a player).

To start investigating how this first prototype could be enhanced and what could be the benefits of this interactive game as compared to a non-interactive version, we organized a brainstorming with several colleagues. Many additional features were proposed. Some concerned the use of feedback to enrich the user experience with sounds and sound effects. For example, a particular sound could be played whenever the Wolf moves on in order to give the players a sense of how

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[80] http://accessijeux.com/

[81] http://accessijeux.com/produit/le-petit-chaperon-rouge/

close it is from the grandmother's house. Different sounds could also be played if the players win or lose. Other features concerned the game itself and included random traps that could prevent Little Red Riding Hood from advancing, arbitrary changes of the path length, possibilities to select different levels of complexities, to compute and save each player's score, etc. Finally, some participants suggested that the interactivity could be used to ensure that all players are equally involved with the game: for example, one of each player's fingers could be tracked so that the system only responds when a particular player is picking up a new card.

These propositions are currently being further investigated by a Master's student (Audrey Cabrolier), in collaboration with teachers and students from the IJA. The second version of the prototype relies on the Tangible Box (Figure 6.8). A number of interaction techniques are being designed to enable users to pick up cards, retrieve their names, etc. Interestingly, the prototype will provide different feedback according to the users' expertise: for example, at the very beginning of the game, detailed instructions are given about the rules of the game and the interaction techniques; as the game evolves, instructions are less and less detailed.

Figure 6.8. Prototype of a collaborative board game, based on the Tangible Box. (Photo by Audrey Cabrolier).

4.3 GEOVIS AND PHYSICALIZATIONS: TOWARDS GEOPHYSICALIZATIONS?

The increasing number of online and interactive geostatistical visualizations makes it necessary to develop accessible prototypes that can guarantee visually impaired users an equal access to these representations, or at least to their content. However, up to now, most prototypes of interactive maps for visually impaired people have been designed to display Orientation & Mobility maps or maps that represent the different states of a country, but very few allow users to access thematic maps (e.g. [6,352]). Besides, these prototypes of thematic maps were all digital. There is therefore a lack of research concerning the development of hybrid prototypes that could support the display of geostatistical data. In addition, we reviewed in 3.5 research related to the field of data physicalizations. Even though these studies were mainly concerned with sighted users, the design of prototypes for visually impaired users may build on these first investigations.

The literature concerning data physicalizations or geostatistical maps for visually impaired users is much more restricted. However, the iSonic prototype developed by Zhao et al. [352] may serve as a good starting point as it not only describes a number of functionalities for the exploration of georeferenced data, but also provided a framework, called Action-by-Design-Component, to help design auditory interfaces for analytical data exploration. In particular, the authors discussed a set of actions that should be supported by these auditory interfaces: gist, navigation, situating, searching, filtering, details-on-demand, selecting and brushing. Although the description of each of these actions was focused on the use of audio feedback only, it might be worth investigating to what extent physical representations may support (and eventually facilitate) such actions. For example, listening to a gist of the data may be equivalent to exploring a physical representation of the data using both hands; the combination of audio gist with tactile exploration may also prove particularly efficient.

Focusing on tabletop TUIs, the study by Jones and Maquil [125] can also be a good starting point for the design of tangible geostatistical maps for visually impaired users. On the basis of the potential of TUIs for geospatial learning activities, they investigated the design of tangible objects and interactions for exploring a digital map. Eight novice users were asked to perform a number of tasks using a set of tangible objects, without being given any information about how to use these objects. The objects could be used to perform the following actions: panning, zooming, activating layers, prioritizing layers and retrieving a specific piece of information. Based on the analysis of participants' actions and comments, several guidelines were proposed for the design of geospatial tangible interfaces, concerning the understanding of cartographic elements (input techniques and feedback for panning and zooming, use of legends, manipulation of layers), the objects' manipulation (design, labelling, feedback about whether the object manipulation is effective, etc.) and the importance of "offline" spaces, which enable users to explore the tangible tabletop in a non-interactive manner, for example by reorganizing the tangible objects on the edge of the table or by touching the screen. Although the focus here was more on the manipulation of tangible objects to interact with a digital representation, it might be interesting to combine these findings with the use of tangible objects that represent georeferenced elements (as it is the case in BotMap).

WORK IN PROGRESS: DESIGN OF A GEOSTATISTICAL TANGIBLE MAP

Based on these considerations, we began investigating the development of a geostatistical tangible map that would include three main components: 1) a physical and dynamic "pan & zoom" map (as in BotMap); 2) an actuated bar chart (inspired by [68,293]); 3) a set of interaction techniques inspired by the framework proposed in iSonic [352], that rely on the manipulation of tangible objects (as studied by Jones and Maquil [125]). The usability and feasibility of physical "pan & zoom" maps was demonstrated through the three user studies conducted with BotMap. As for the actuated bar chart, a proof-of-concept prototype was developed by Ludovic Lesur [163] in the framework of his internship and of the AccessiMap project. The underlying idea is that users would be able to filter and select which information they want to display on the bar char–these pieces of information being associated with one (or several) points of interest.

The prototype has been developed as a stand-alone device composed of two sets of four actuated bar charts. It is therefore possible to either use the eight bars as a single bar chart, or to use them separately. Each module is connected to a PCB and can be controlled using a Java application. Whenever a module needs to be refreshed, the corresponding four values are sent to the module's microcontroller, which controls the movement of each bar. Each bar is made out of Lego and is mainly composed of a step motor and a gear rack, whose maximum height is 6.5 cm. As can be seen in Figure 6.9, a push-button is placed at the bottom of each bar: whenever the user presses it, the corresponding value is read out.

In addition, three features have been implemented. Firstly, a calibration procedure is run every time that the device is turned on and can be activated on demand to readjust the bar charts. Secondly, each bar can "vibrate" by moving up and down with a high frequency, and both the frequency and the range of motion can be adjusted dynamically. With a large range of motion and a low frequency, this creates a "swing" movement that can be easily detected when touching the bars. Thirdly, three display modes have been implemented: *absolute* (the minimum and maximum values corresponding to the lowest and highest possible bar positions are set by the user); *percentage* (the highest value is set to the highest position of the bar and stands for 100%, and the remaining bars are changed accordingly, as a measure of ratio between their value and the highest value)*, maximum contrast* (the bar chart is scaled so that the minimum value corresponds to the lowest possible position and the maximum value corresponds to the highest possible position).

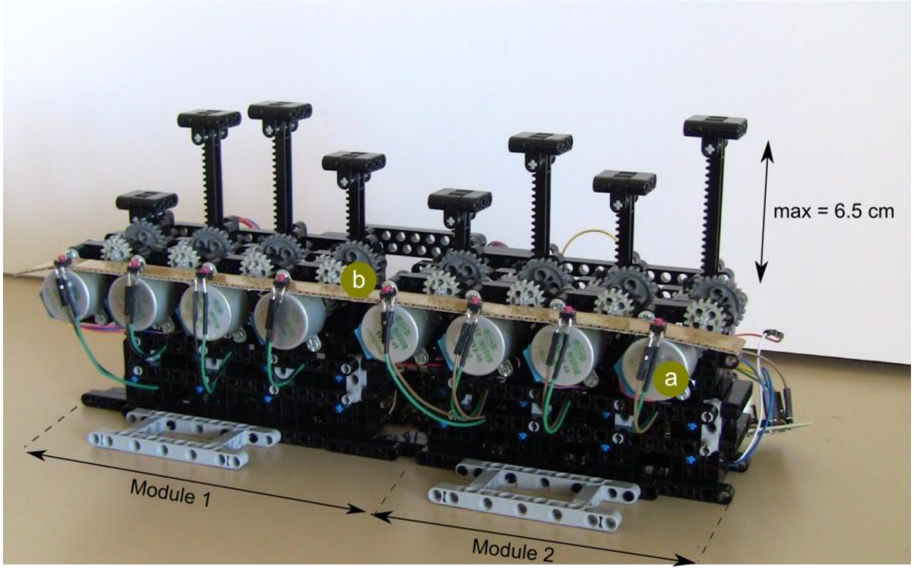

Figure 6.9. Prototype of an actuated bar chart. The bar chart is composed of two modules of four bars each. Each bar is mainly composed of one step motor (a) and one button (b).

As for the third component, which enables users to manipulate tangible objects to select which information to display, we describe in Appendix D an ongoing project on which two Master's students (P. Mesnigrente and L. Lesur) already worked, under the supervision of M. Macé and myself, and in collaboration with SphereL[82], a company specialized in the design and implementation of technological solutions. The aim was to design a set of small and stable tangible objects that could be tracked by the interactive table we used for BotMap, therefore avoiding possible hand occlusions (currently, the table cannot be used to track small objects). Although this is still an ongoing project, initial results showed the feasibility of the proposed approach: small LEDs are embedded into the objects, which enable the application to not only detect the position of the objects, but also to identify them.

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[82] http://spherel.com/

One scenario that would be particularly interesting to study is election results (as we already mentioned in Chapter 3, 8.5.1). Election results are very often represented on maps, which allow people to quickly identify spatial trends, and optionally to select which information to display. Our prototype could give visually impaired users the opportunity to access these maps, but also to analyze them in an interactive manner. For example, users could select one landmark and the results of the main political parties could be displayed on the bar chart. Users could also interact with the system to compare the results of two different towns, to select which political parties' results they want to display on the bar chart or to compare results according to the voters' age or education level, for example (see Figure 6.10).

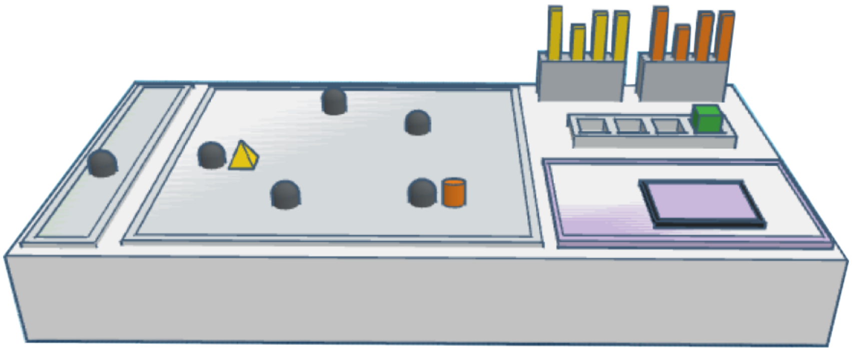


Figure 6.10. Example of a "geophysicalization" based on BotMap and the actuated bar charts. Users could select a town by placing a tangible object next to the robot representing the said town (yellow triangle and orange cylinder) and select which information to display (green cube). For example, the results of the four main political parties could be displayed on one bar chart. Users could also pan (using a tangible viewport, as shown at the bottom right of the figure and discussed in Chapter 5, 7.4.3), and zoom (slider on the left).

We believe that this enhanced BotMap prototype could serve as a platform to address a number of research questions that have not yet been addressed for visually impaired users. Concerning the design of data physicalizations, the actuated bar chart could be used to investigate various interaction techniques to retrieve the values, compare them and eventually compare different sets of values across different regions or the evolution of a set of data over time. It would also be interesting to compare the usability of the actuated bar chart as compared to other technical solutions (e.g. use of a screen reader to navigate within a spreadsheet), for example, in terms of legibility, understanding and memorization. As we already discussed, the prototype could also serve as a platform to design tangible menus and interaction techniques, for example, using a similar methodology than the one proposed by Jones and Maquil [125]. In the long-term, and based on ongoing projects of collaborative TUIs, the prototype could therefore serve as a platform to design and investigate the design of (collaborative) "*geophysicalizations*" for visually impaired users.

CHAPTER 7

CONCLUSION

Heureusement que j'étais arrivé parce qu'on s'était tout dit et qu'on avait atteint un point dans les confidences où il allait être très difficile d'aller plus loin et au-delà à cause des embouteillages intérieurs.

Romain Gary (Emile Ajar). Gros-Câlin.

Chapter structure

1. Pros and cons of tangible maps and diagrams for visually impaired users
2. How "tangible" are the interfaces that we developed?
3. A far-reaching agenda for further research

In the previous chapter, we reviewed the contributions of this thesis, discussed to what extent the interfaces that we developed are related to other interaction paradigms, and proposed a number of perspectives for further research. In this final chapter, we question the pros and cons of our interfaces when compared with existing approaches, and reflect upon whether these interfaces are "tangible" enough to provide evidence in favor of non-visual tangible interaction. We conclude by providing a few remarks on the challenges that remain to be addressed by the community in order to catch up with the research on, and development of, visual interfaces.

1 PROS AND CONS OF TANGIBLE MAPS AND DIAGRAMS FOR VISUALLY IMPAIRED USERS

One of the initial points of this thesis concerned the growing gap between sighted and visually impaired people's access to graphical representations, which can mainly be explained by the fact that research projects on the accessibility of interactive maps and diagrams have mainly focused on purely digital approaches or on interactive tactile maps and diagrams, preventing visually impaired people from accessing physical and updatable interfaces. However, such interfaces are necessary to give visually impaired people the possibility to independently explore graphical representations that are similar to those used by sighted people, and to interact with them in the same way sighted people do.

A few alternatives exist that do support physical and updatable representations, but they are either extremely expensive (raised-pin displays [350]) or offer a slow and limited way to update the representation (maps that are 3D-printed based on users' inputs, as in Linespace [292]). Therefore, new approaches must be considered, and TUIs, due to their inherent physicality and reconfigurability, appeared to us as being an interesting means to bridge the gap between the non-visual digital/updatable and physical/static worlds.

Consequently, the aim of this thesis was to get a first idea of how "good" tangible maps and diagrams for the visually impaired could be. We considered different solutions (e.g. actuated and non-actuated), tasks (e.g. exploration and reconstruction) and graphical representations (e.g. timelines and maps), which lead us to the development of three prototypes. Due to their specificity it is difficult to embrace them as a whole in order to draw conclusions about the relevance of TUIs for visually impaired users in general. However, taken individually, they shed light on a number of advantages and limitations of using tangible interaction to make maps and diagrams accessible to visually impaired users, compared to existing approaches.

The Tangible Reels were mainly designed to support the reconstruction of tangible maps and diagrams, a task that is neither supported by digital prototypes nor by other types of hybrid prototypes (interactive tactile maps, raised-pin displays or Linespace). Therefore, the main question is whether being able to reconstruct a map or a diagram presents any advantage. In an educational context the answer is obvious, as shown by the large use of updatable tactile graphics (e.g. based on corkboard and magnetic board) in specialized education centers. Outside schools however, we believe there is no clear answer. The action of reconstructing something may facilitate memorization and comprehension, but neither the literature nor our thesis provides clear empirical evidence (see Chapter 6, 3.1 for a more detailed discussion on that topic). Another advantage may lie in the fact that if the map or diagram is composed of tangible objects, then it can be reconfigured to display dynamic changes, a task that is not supported by (interactive) tactile maps. However, one limitation of our work is that we did not specifically address this question. In the current implementation of the prototype, once the map or diagram is reconstructed, users can only explore it (and optionally annotate it). Overall, leaving aside educational purposes, it seems that if the map or diagram is not meant to be updated, then using tangible interaction may not be the "best" option, as tangible maps and diagrams built with Tangible Reels only cannot reach the same degree of complexity and expressiveness as (interactive) tactile maps or raised-pin displays.

In that sense, the Tangible Box is a promising approach: not only does it present the same benefits as tactile maps and diagrams (and notably the possibility to physically display areas), but it also partially overcomes their main limitation, by making it possible to reconfigure some parts of the graphical representation using tangible objects. In addition, similar to the Tangible Reels, it supports tasks that require the user to physically manipulate the elements of the representation, which is beneficial for developing learning activities. Although the prototype does not offer the same degree of interactivity as interactive tactile maps, as users cannot simply perform double-taps to retrieve the name of an element, we discussed in Chapter 4, 6.4.1 various ways in which this limitation could be compensated (e.g. using a smartphone placed above the Tangible Box). In fact, one can consider the Tangible Box as an augmented interactive tactile map prototype, and, in that sense, it could possibly be considered to be a "better" solution than existing interactive tactile map prototypes and, possibly, than some digital prototypes that cannot be used to display expressive, complex, and/or updatable graphical representations. Nevertheless, it only offers a limited dynamicity compared to raised-pin displays–the dynamicity of which, however, comes at a very high cost compared to the Tangible Box–and to Linespace.

BotMap offers a higher degree of dynamicity, as the tangible objects move by themselves, and can therefore be used to access large amounts of data. As such, it opens various perspectives, notably concerning the accessibility of geostatistical maps. One of the main limitations of this prototype is the fact that only points can be represented, which considerably restricts the type of graphical representations that can be accessed using this system, compared to interactive tactile maps, raised-pin displays or Linespace. However, giving users the possibility to physically manipulate the robots, as we discussed in Chapter 6, 3.4, could be one advantage of BotMap over other types of hybrid prototypes. Compared to digital prototypes, not only could BotMap be as expressive as most of them, by implementing additional ways to explore the representation (Chapter 6, 4.1.3), but it would allow users to access more complex representations through panning and zooming, while supporting two-handed exploration, though at a higher cost.

The following figure (Figure 7.1) is an attempt to summarize how the prototypes differ to or complement existing approaches of hybrid prototypes. Although we did not specifically investigate the possibility for users to physically manipulate the BotMap's robots, such an aspect is one core property of Swarm User Interfaces, and we therefore considered BotMap to be highly manipulable.

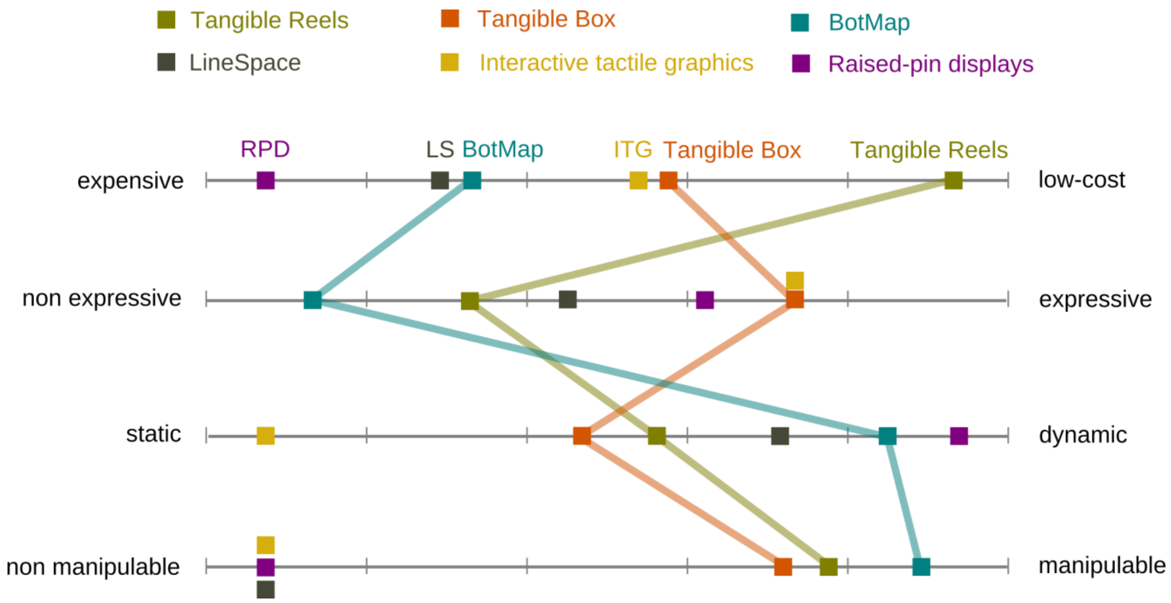


Figure 7.1. Pros and cons of our interfaces compared to existing hybrid prototypes. For the sake of clarity, we only displayed lines between factors for the interfaces that we developed.

2 HOW "TANGIBLE" ARE THE INTERFACES THAT WE DEVELOPED?

As we previously discussed, it is difficult to state how "good" tangible maps and diagrams for visually impaired users can be based on our thesis, notably due to the specificity of the interfaces that we developed, which make them difficult to embrace as a whole. Another aspect that is worth discussing is whether these interfaces are "tangible" enough to provide evidence in favor of non-visual tangible interaction.

Ullmer defined TUIs as "a genre of human-computer interaction that uses spatially reconfigurable physical objects as *representations* and *controls* for digital information" [306]. In this thesis we especially focused on the first part of this definition (i.e. objects as *representations*) and did not particularly address its second part (i.e. objects as *controls*), raising the question of whether the interfaces that we developed can really be considered as being tangible.

The reasons why we focused on tangible objects that represent information instead of (or in addition to) tangible objects that act as representations *and* controls are mainly practical. At the very beginning of this thesis we began to investigate how to make digital maps and diagrams tangible and quickly came across two design challenges that had to be addressed as a matter of priority: how to make the tangible representation stable, and how to make it sufficiently expressive to be useful. If no suitable solutions could be found, then there was no point in investigating how users could manipulate the tangible objects to interact with the digital representation. For this reason, the first study that we conducted (see Chapter 3, 3) aimed to assess whether maps built with Tangible Reels were stable and legible and did not rely on any interactive features. Thereafter, we investigated different interaction techniques and feedback to guide users during the reconstruction of the map–an aspect that we also evaluated, see Chapter 3, 6.

Probably the next logical step would have been to investigate how to make use of tangible objects as controls, for example to enable users to physically annotate or edit the map. However, at that time, we were somewhat frustrated by the degree of dynamicity of the prototype and thought that even if we implemented techniques that would allow users to edit the map or to pan and zoom, the process of manually repositioning the objects would remain cumbersome. Also at that time we were reflecting upon the use of actuated tangible objects (to have more dynamic representations) and on the use of tangible objects on top of raised-line graphics (to have more expressive representations). We found these two approaches promising and decided to focus our efforts on the development of BotMap and, later on, of the Tangible Box. Nevertheless, a second version of the Tangible Reels was developed for the educational workshop that we organized, and two additional features were implemented (construction and annotation), which increased the "tangibility" of the interface, but that we did not develop further for lack of time. With BotMap, only the sliders used for panning or zooming act as representations and controls; however, we discussed in Chapter 5, 7.1 and in Chapter 6, 3.4 how the prototype could be improved by allowing visually impaired users to directly interact with the tangible objects. As for the Tangible Box, we attempted to develop applications where the tangible objects act as both representations and controls (see the Talking clock for example, Chapter 4, 5.1). We also considered the use of tangible menus, where the tangible objects act as controls rather than representations (Chapter 6, 3.3).

To sum up, we acknowledge the fact that one main limitation of our work is that the interfaces that we developed are not as "tangible" as they could (or should) have been. Nevertheless, we believe, as discussed in Chapter 6, 4.1, that further research and development could make them more tangible, and therefore even more relevant compared to other types of map and diagrams prototypes. Figure 7.2 illustrates for each interface how far there is to go to make it fully tangible.

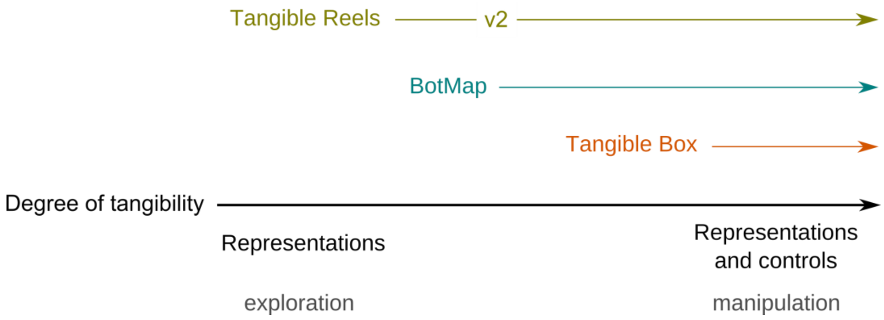


Figure 7.2. How tangible are the interfaces that we developed.

Once again, this thesis was the first formal investigation of tabletop tangible maps and diagrams for visually impaired users and we could not address all design challenges at once: we chose to focus on the ones that appeared to us as being the most important, and provided a number of solutions that will certainly facilitate the design of future tabletop TUIs for visually impaired users. By doing so, we think that researchers and/or developers will be able to focus their efforts on the design of interaction techniques that take full advantage of the reconfigurability of the tangible representation, rather than on the design of the tangible representation itself.

3 A FAR-REACHING AGENDA FOR FURTHER RESEARCH

We would like to conclude this thesis with two (personal) remarks concerning the research on and development of accessible interactive graphical representations for visually impaired users.

3.1 GUARANTEEING EQUAL ACCESS TO INFORMATION

The first is related to the urgent need for the community to catch up with the degree of interactivity of visual representations, in order to guarantee an equal access to information. Up to now, most research has mainly focused on very simple graphical representations composed of only a few elements. Although this might be sufficient for educational purposes, this is not sufficient for real-life situations where visually impaired users need to access large and complex sets of data. As infographics and thematic maps become more and more popular and gradually replace textual information, the need to develop affordable prototypes that support complex and updatable graphical representations is becoming more and more critical.

To guarantee an equal access to information, another imperative is to provide functional equivalence between interactive representations for sighted users and those for visually impaired users. However, up to now efforts have been more commonly focused on the content of the representation rather than on the means of interaction with content (e.g. annotating, highlighting, etc.). Obviously, some research did investigate these aspects (see [352] for example), but compared to the number of prototypes that have been implemented, their number is relatively small. In addition, providing users with such interactive features could also help them to compensate for the lack of visual feedback: a good example is a "gist" feature [352], which can be functionally equivalent to quickly scanning a map or a diagram with the eyes to identify patterns or to gain an overview of the representation. Another benefit of implementing interactive features is that they can be used to adapt the content to the low resolution of the prototype, therefore enabling users to access the same amount of information as sighted users, though using different views instead of only one. For example, panning and zooming allow users to sequentially explore different (sub-) parts of the representation, and filtering allows them to only display a subset of the data.

We acknowledge on several occasions the differences between the visual system and the haptics system, which partly explains why prototypes of interactive maps and diagrams do not offer the same complexity as, for example, online and visual graphical representations. This is particularly true for digital maps and diagrams prototypes that provide a single point of contact and/or no tactile feedback. Concerning interactive tactile maps and diagrams, their lack of updatability makes it difficult (but not impossible) to implement features such as filtering or annotating, which would allow functional equivalence. However, we also somewhat suspect that the simplicity of the graphical representations that have been considered, be it in terms of content or in terms of interactivity, might be due to the lack of a far-reaching perspective regarding the true potential of accessible graphical representations for visually impaired users.

Evidently, we acknowledge the usefulness and necessity for visually impaired people to access Orientation and Mobility maps, but we are also convinced that providing them with access to geostatistical maps that would enable them to "reveal unknowns" on their own might be as worth considering, especially in the context of the actual information crisis. Furthermore, the (ongoing) debate on the spatial abilities of visually impaired people, which we mentioned in Chapter 1, 2.2 and Chapter 5, 5.4.1, may also still influence what type of tasks and graphical representations researchers are willing to make accessible to visually impaired users. However, given the increasing number of empirical evidence in favor of the amodal theory of spatial representation [174], which stipulates a functional equivalence between mental representations built from tactile or visual perception, we believe that future research on accessible maps and diagrams should no longer be restricted by the presumed limited spatial abilities of visually impaired users.

3.2 EMBRACING AND INITIATING INNOVATIVE INTERACTION PARADIGMS

The second remark is related to the approaches that have been investigated so far by researchers working on the accessibility of interactive maps and diagrams. Given the extent of literature on tangible interaction for sighted users, it is very surprising to see that this field of research has barely been considered for visually impaired users. The most advanced prototype of TUIs was proposed by McGookin et al. [196], in 2010, that is to say, more than ten years after the publication Tangible Bits [113]. This "disparity" is particularly surprising considering the inherent physicality of TUIs, which directly echoes traditional approaches to make maps and diagrams accessible to visually impaired people, such as tactile graphics and small scale models.

Similarly, the field of data physicalizations, which clearly relates to the accessibility of graphical representations for visually impaired users, has not yet been fully apprehended by the community and, equally surprisingly, was not initiated by it. And yet there is no doubt that empirical findings, theories or implementations related to physicalizations for visually impaired users could also benefit physicalizations for sighted users. We hope that the community working on developing accessible maps and diagrams will embrace the field of data physicalizations more quickly than the field of TUIs. Taking into account our previous comments on far-reaching perspectives, we also hope that, in the future, research on maps and diagrams for visually impaired users could not only build on existing approaches and interaction paradigms for sighted users, but also break new ground and propose innovative approaches from which researchers working on visual representations might draw inspiration.

In that sense, we believe that this thesis, and notably BotMap, was one step towards the development of a far-reaching agenda that will consider various and complex graphical representations and tasks, and embrace and initiate innovative approaches. More precisely, with BotMap: 1) we plan to give visually impaired users access to geostatistical maps, and notably election maps, a type of graphical representation that has rarely been studied; 2) we investigated non-visual panning and zooming, a feature that has not been formally investigated previously; 3) we used small robots on top of an interactive tabletop to display maps–although the concept of actuated tabletop TUIs is not new, in BotMap most elements are physically embodied, as in Swarm User Interfaces, a type of interface that was only formally defined while we were developing BotMap; 4) we propose the concept of "geophysicalizations", which will give (visually impaired or sighted) users access to physical, but also dynamic maps, along with interaction techniques inspired by research on GeoVis.

3.3 BRIDGING THE GAP BETWEEN NON-VISUAL PHYSICAL AND DIGITAL WORLDS: NEXT STEPS

Throughout this thesis, we proposed a number of solutions to address design challenges related to the development of tangible tabletop maps and diagrams for the visually impaired. We notably developed three tangible interfaces that enable visually impaired users to access a variety of graphical representations and to perform diverse tasks, such as reconstructing a bar chart or exploring a "pan & zoom" map: the Tangible Reels, the Tangible Box, and BotMap. By doing so, we demonstrated the potential of using tangible interaction to make graphical representations accessible to visually impaired users and provided a first formal investigation of the possibilities and pitfalls of this approach. We also described in detail the design rationale of these interfaces, as well as their implementation and the results from the user studies that we conducted.

In addition, in the previous sections we identified a number of short-term and long-term perspectives to continue this work (see Chapter 6). Some concerned the improvement of the interfaces and drew especially on related interaction paradigms (constructive assemblies, token+constraint and Swarm User Interfaces); others were not specifically related to the interfaces that we developed but included the use of audio and haptic feedback as well as the development of collaborative TUIs and geophysicalizations. We also discussed how the interfaces that we developed could serve as a platform to conduct user studies that would investigate, for example, the benefits of using a TUI to acquire knowledge, but also to design and evaluate innovate interaction techniques, for example to interact with tangible menus.

Altogether, we hope that the pieces of information related to the design, development and evaluation of the three interfaces as well as the perspectives that we identified will facilitate and encourage the design and deployment of tangible maps and diagrams for visually impaired (and sighted) people, and, ultimately, empower visually impaired people by giving them the opportunity to independently explore and interact with complex data in the same way that sighted people do.

APPENDIX

A. Tangible Reels: supplementary material
B. The Tangible Box: supplementary material
C. BotMap: supplementary material
D. Work in progress: designing small and stable objects
E. Scenarios for the Cellulo project
F. Résumé détaillé (français)

APPENDIX A
TANGIBLE REELS: SUPPLEMENTARY MATERIAL

A.1. State-machines

Figure A. 1 shows the state-machine summarizing how the construction if handled by the application. Green labels indicate feedback; purple labels indicate instructions; black labels indicate events detected by the application or conditions. As long as lines need to be built (IDLE), users are asked to place a new Tangible Reels (TR) on the table. As soon as a new TR is detected, users are guided until it is correctly placed (GUIDING). Then, they must place a new TR on the table (WAITING), referred to as B, before connecting it to another Tangible Reel, referred to as A (CONNECTING). As soon as the system detects that A and B are connected, users are guided to place B (GUIDING). The procedure is repeated until all lines are built. Then, a similar procedure is repeated to enable users to correctly position points (WAITING POINTS and GUIDIND POINTS).

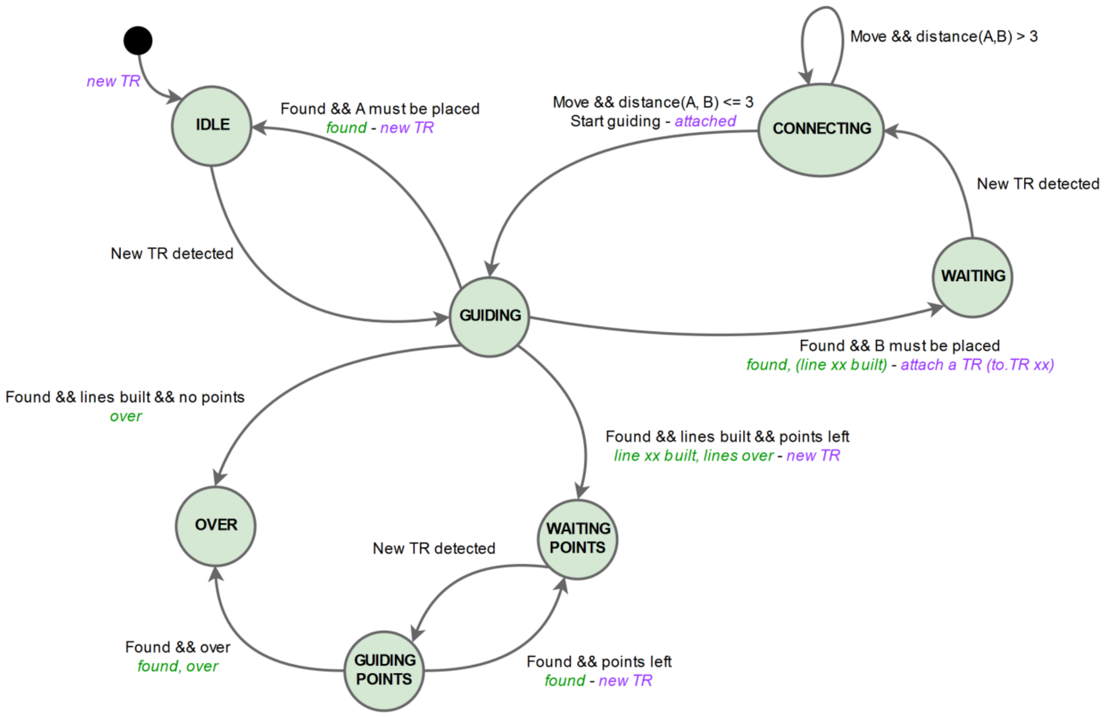


Figure A. 1. State-machine summarizing how the construction is handled by the application.

Figure A. 2 shows the state-machine summarizing how the two-step guidance technique is handled by the application. Green labels indicate feedback. Labels in italics indicate actions performed by the application such as starting or stopping timers. When the tangible object is far from the target (i.e. the place where it must be positioned), "coarse" guidance instructions are given (COARSE). When the tangible object is close to the target, "fine" guidance instructions are given (FINE). If an object is not detected (STAND_BY) for a certain amount of time (IN_AIR), appropriate feedback is given. When an object is in the right place (CONFIRMING), the system waits for 1.5 seconds before giving the next instruction (FOUND) (in case the user would continue moving the object). *f* is the maximum distance between the object and the target for the object to be considered as correctly positioned.

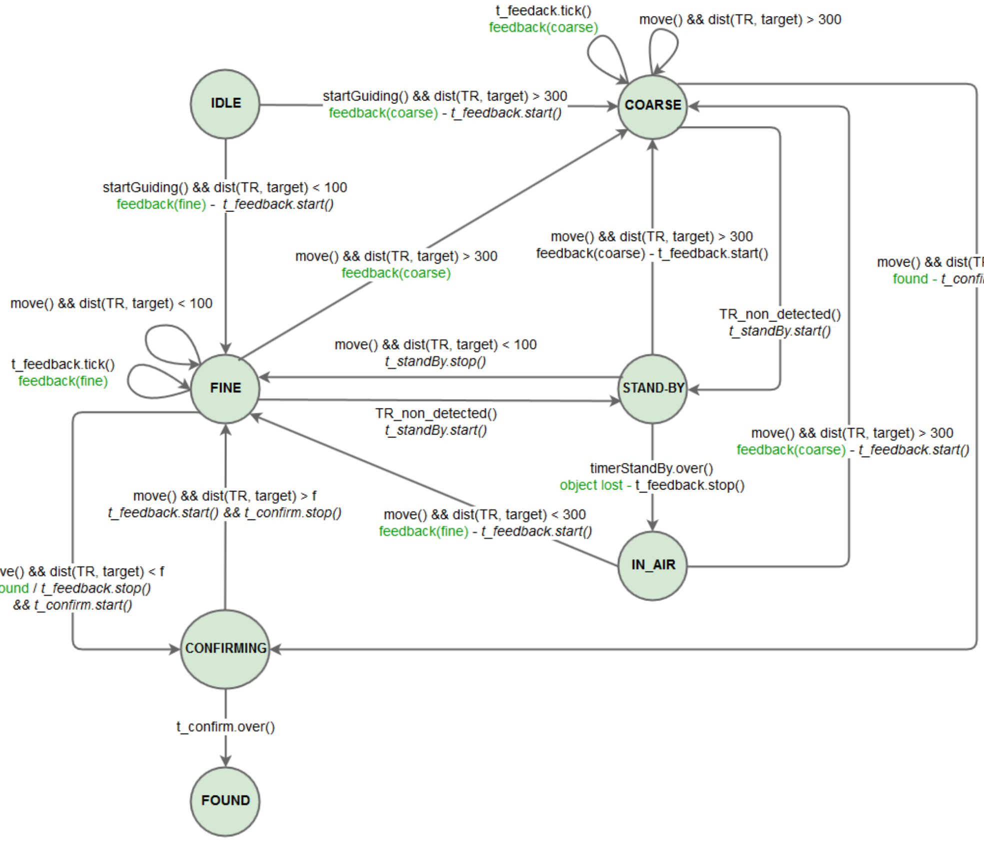


Figure A. 2. State-machine illustrating the two-step guidance technique.

A.2. Map drawings

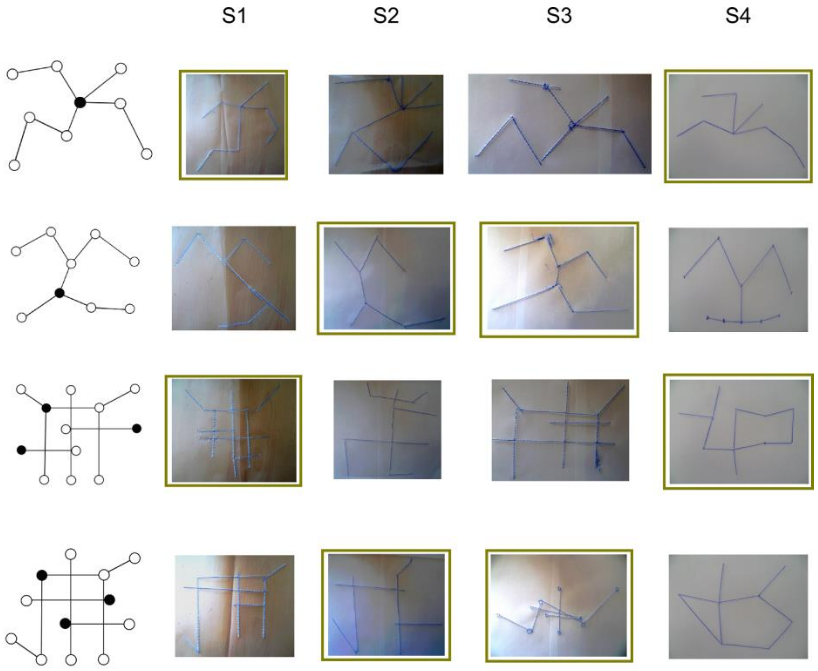
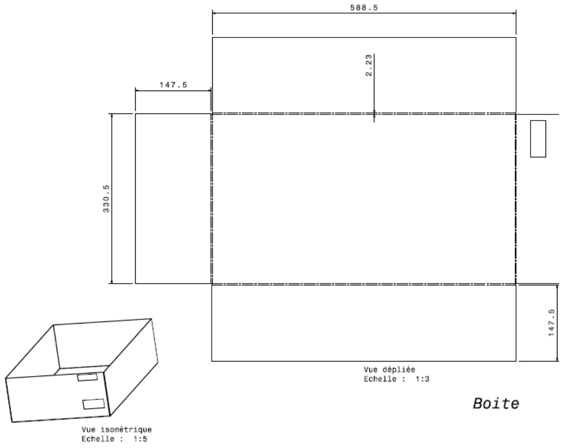
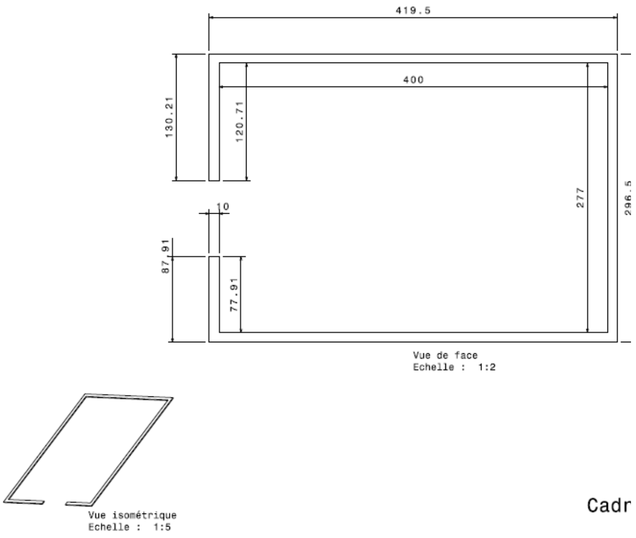


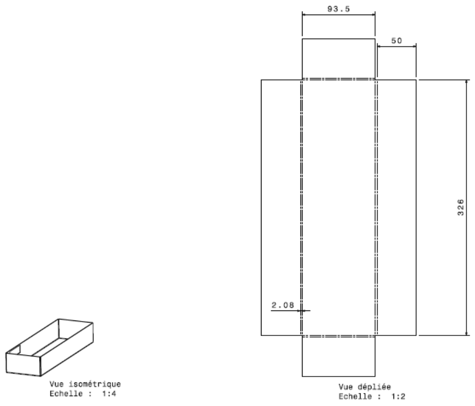
Figure A. 3. Map drawings from the pre-study (Chapter 3, 3). Green frames shows drawings of map built with Sucker Pads.

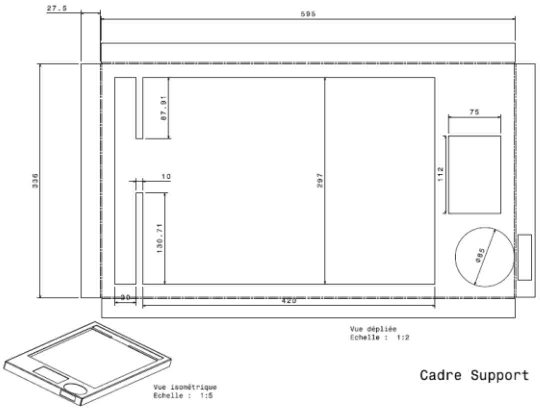
APPENDIX B
THE TANGIBLE BOX: SUPPLEMENTARY MATERIAL

B.1. Schematics and dimensions









B.2. Cost

Element	Dimensions	Cost (in euros)
Aluminium plate	Cf. Figure B.1	50
Raspberry and case	85 x 56 x 18 mm	40
PiCamera	32 * 32 * 22	25
Wifi Routeur	57 * 57 * 18	25
Speaker	85 x 85 x 38 mm	15
Keyboard	112 x 75 x 10 mm	10
Magnetic sheet	Cf. Figure B.1	15
Magnets	-	10
Cables	-	20
LEDs	-	15
3D-printed elements	-	15
Others (screws, springs, etc.)	-	40

B.3. Applications proposed during the brainstorming

#	Subject	Description
1	English	A raised-line map with the main boroughs of NYC. A tangible object with a "yellow cab" hat can be moved above the boroughs and their name is given. Possibility to give instructions (e.g. "go to Manhattan") and also to guide the student ("go north, through the bridge"). Then possibility to have questions: "which bridge is located between A and B?") > To learn the boroughs, but also to help students learning directions.
2	Maths	Cf. description given in Chapter 4, 5.3. Same idea but with Thales as well.
3	Biology	A graphic with the heart, the arteries, etc. Students need to move a tangible object along the blood flow.
4	Maths	Conversion tables. One token = one number. Students would need to place the numbers in the right cell of the tables. Possibility to give feedback, or to ask questions such as "how many meters in two kilometers?" and to check the answers.
5	Biology	A body part chart. Students would need to move one tangible object above the different parts to retrieve their names and/or to answer questions asked by the system (e.g. where is the head?"). Possibility to use a menu to select between muscles, bones, organs, etc.
6	History	Cf. description given in Chapter 4, 5.2
7	Geography	A map of France/Europe. One tangible object = one city. Students would need to place all cities in their right place and then the application would give feedback. Another possibility would be for the system to ask the students to place the city one after another, and to give feedback every time.
8	Geography / O&M	A map with different routes (motorway, local road, etc.). A tangible object (with a "car" hat) can be moved along the routes and the application indicates whether it is a motorway or a local road, and gives instructions ("take the next exit, you are now on a national road").
9	Geometry	Students would be guided to reconstruct a geometric shape. (proprioceptive feedback could be beneficial)
10	Arithmetic operations	Students would be helped (and possibly guided) to write additions, subtractions, etc. E.g. "line up the tens and units".
11	Tables	Helping students learn how to read tables and notably cross-tabulations. One table is drawn on the graphic, and students are asked to place one object in the right cell. For example, if rows = colors and lines = shapes, the questions could be: "where is the red circle?".
12	Tables	Helping students learn how to navigate a table: students would need to move a tangible object by following instructions such as "go 4 cells to the right".

B.4. Template for describing Tangible Box applications

Overall characteristics	
Name	*e.g. Trigonometric ratios*
Subject	*e.g. Maths*
Purpose	*e.g. learning how to compute sine*
Users	*e.g. Middle-school, low-vision*
Graphical representation	Type: *e.g. a set of triangles + one line for the formula*
	Content: -
List of activities	Activity 1: *e.g. explore* Activity 2: *e.g. find the opposite side/ hypotenuse* …
Dependencies between activities	e.g. *independent*
Switch between activities	*e.g. keyboard "plus" and "minus" buttons*

Material					
Support	*e.g. German Film*				
Tangible objects / components					
Activity	Type	Info. / Menu	Name (Info. or menu item)	Hat / Others	Interactivity
2	*e.g. Token*	*e.g. hypotenuse*	*e.g. hypotenuse*	*e.g. Braille, "h"*	*e.g. shaking*
2	*e.g. Token*	*e.g. opposite side*	*e.g. opposite*	*e.g. Braille, "o"*	*e.g. cursor*

Activity	**ID:**
Type	*e.g. Exploratory*
Tasks involved	*e.g. Exploration*
General description	*e.g. users must move the "selection" tool next to each side of the triangles to retrieve pieces of information…if they are close to the hypotenuse > F1.*
List of feedbacks	F1: *e.g. "this is the hypotenuse"* F2: *e.g. "this is the opposite side of angle BAC"* …

APPENDIX C
BOTMAP: SUPPLEMENTARY MATERIAL

C.1. Algorithm to manage robots

In this section, we describe how the BotMap application handles the robots. As the robots cannot be controlled wirelessly, patterns need to be displayed on the screen to make them move, turn or pause. In addition, the robots need to be precisely on the path/line to be able to follow it: we therefore implemented an algorithm that does not require robots to change directions and that only display straight lines segments between the current position of the robots and their goal. To update the map, there are three main steps:

1) Assigning each robot to one landmark or one parking place
2) Identifying potential "collisions" between robots
3) Displaying lines and circles to make the robots move, turn or pause.

ASSIGNING EACH ROBOT TO ONE LANDMARK OR ONE PARKING SPACE

1) If there is not enough robots on the viewport: activate robots
2) If there is too many robots on the viewport, assign parking places to robots

```
Compute list of free parking spaces
Compute the distance between each robot and each parking space
While (there are robots to be parked):
      Find the couple (robot, parking) with the smallest distance
      Assign to the robot the corresponding parking space.
```

3) Assign landmarks to robots

```
Get list of landmarks
Compute the distance between each robot and each landmark
While (there are robots that must be assigned a landmark):
      Find the robot that is the most "isolated"
      Assign to the robot the nearest landmark
```

IDENTIFYING POTENTIAL COLLISIONS BETWEEN ROBOTS

We first compute a list of conflicts, each conflict being defined by a pair of robots (A and B). We consider three types of conflicts:

1) A is on the way of B (conflict type: CURRENT). In that case, A must leave its position before B arrives (i.e. A has the priority).

2) A's goal is on the way of B (conflict type: CORRECT). In that case, B must move before A reaches its position (i.e. B has the priority).

3) A's path and B's path intersect (conflict type: INTERSECTION).

For each type of conflict, we then calculate two positions:

- For the robot that has the priority (i.e. that must move before the other), we calculate the position beyond which the other robot will be able to move safely. Once the robot that has the priority goes beyond that point, we consider that the conflict is resolved.
- For the robot that does not have the priority, we calculate the position that it must not go beyond (otherwise, it may prevent the robot that has the priority to move forward).

The following figure illustrates three "current" conflicts where A is on the way of B (1, 2 and 3) as well as one "intersection" conflict (4):

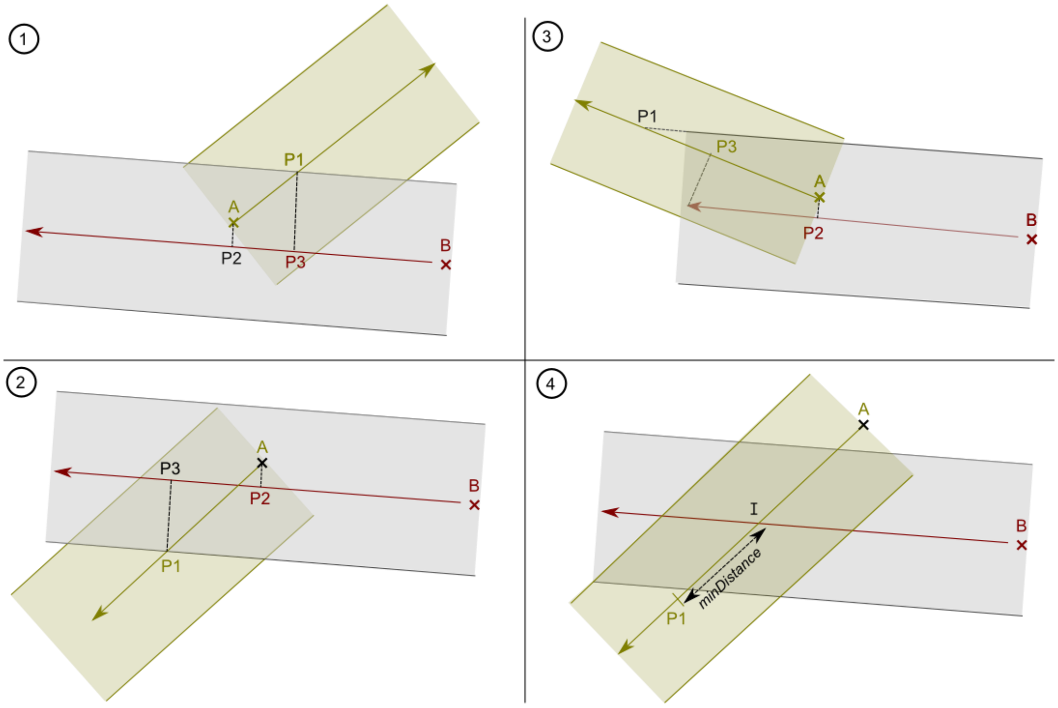


Figure C. 1. Examples of conflicts between two robots. 1, 2 and 3 are "current" conflicts; 4 is an "intersection" conflict. Shaded areas indicate the "safety zone" of each robot: if one robot is in the safety zone of another robot, than collisions may happen. Green labels indicate the position computed for A (the robot that has the priority); red labels indicate the position computed for B (the robot that does not have the priority).

In the first three illustrations, A has the priority and must leave its position before B arrives. Depending on the position and direction of A with respect to B, different positions are computed. For example, in 1), the conflict is resolved when A is beyond P1; meanwhile, B must not go beyond P3. To take into account the robots diameter, we consider that a robot A "is beyond" a position P if there is a certain distance *d_security* between the actual position of A and P. Similarly, to ensure that a robot B does not "go beyond" a position P, there must be a certain distance *d_security* between the actual position of B and P.

The fourth illustration is an "intersection" conflict: since A is the closest to the intersection I, it has the priority. The conflict is resolved when A is beyond P1; meanwhile, B can move as long as distance(BI) – distance(AI) < *d_security*[83].

MANAGING THE ROBOTS

In most cases, all robots are moved simultaneously. However, with the "center before zooming out" functionality, one landmark can be displayed at an inferior zoom level and may be very close to another robot. In that case, to avoid any issue, we move the corresponding robot (called OzoCenter, Figure C. 2, step 1) before moving all robots (step 2) and/or assign to it a temporary goal (step 3):

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[83] This is a simplify equation. In fact, we take into account the position of B when it reaches the end of its path, instead of the current position of B.

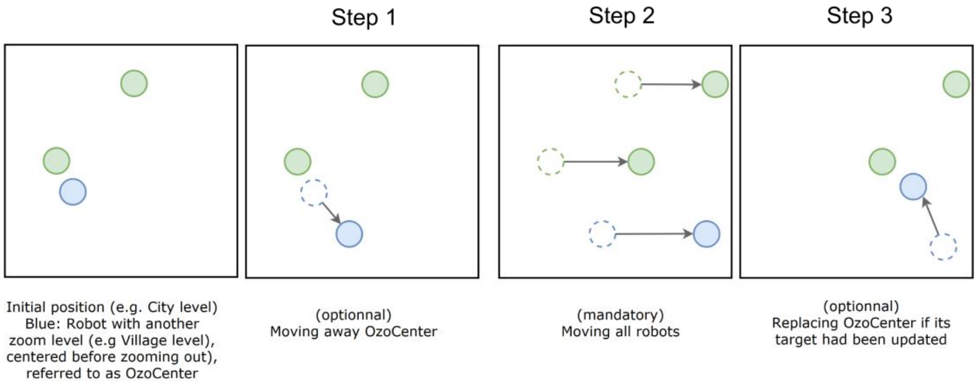

Figure C. 2. Moving the robots can be done in 1, 2 or 3 steps, depending on whether a landmark that is displayed at an inferior zoom level (in blue, referred to as OzoCenter) is too close to another landmark.

To move the robots, we check their position and orientation every 100ms: depending on their state (see Figure C. 3), different patterns are displayed under each robot to make them move (by displaying then translating a line of a certain length), turn (by displaying a colored circle), or pause (by not translating the line and waiting for the robot to reach the end of the line):

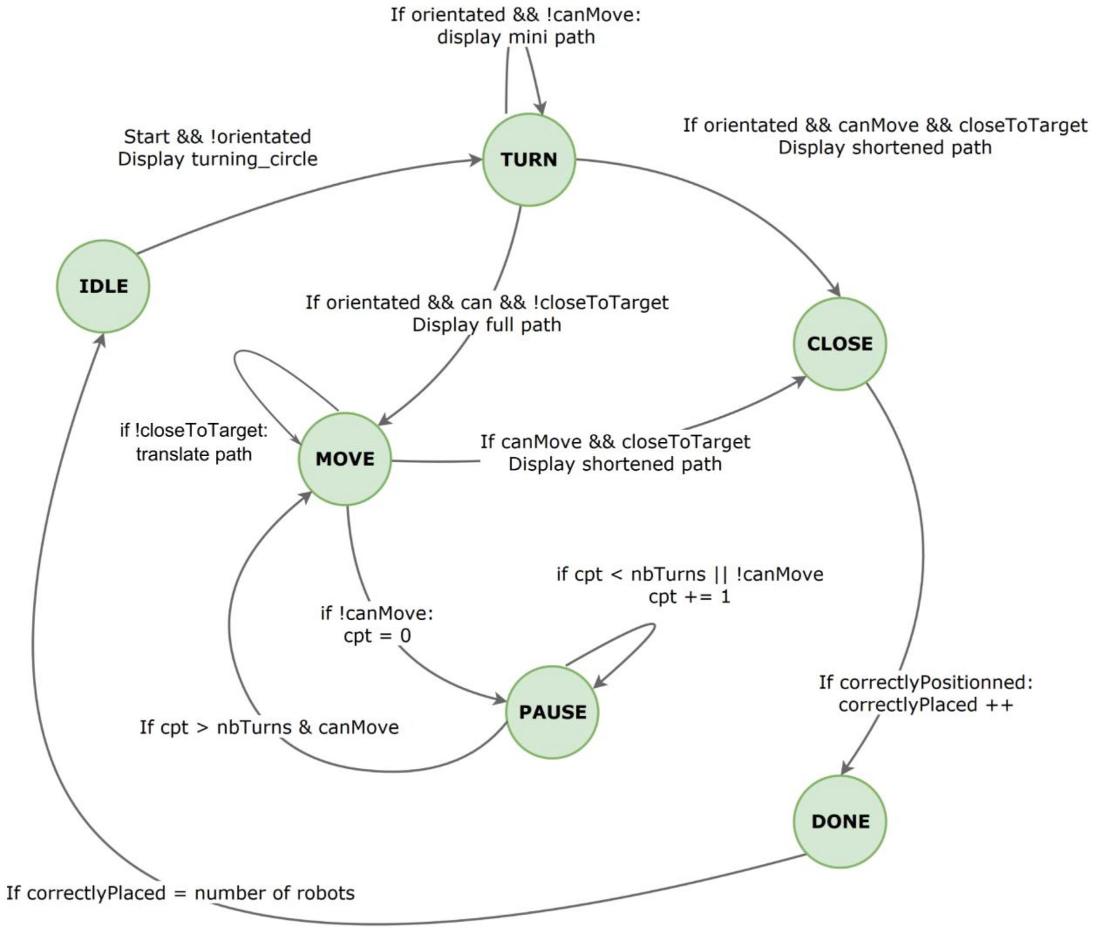

Figure C. 3. State-machine summarizing how the application handles the robots.

C.2. Questionnaires

Questions marked with a * had to be answered on a 5-point Likert scale.

Questionnaire	Questions
Questionnaire 1 : User profile	Age
	Gender
	Professional activity
	Last diploma obtained
	Age at onset of blindness
	Residual perception?
	From 1 to 5, do you regularly use maps? (1 = never, 5 = very often)*
	From 1 to 5, did you use maps at school? (1 = never, 5 = very often)*
	What sort of maps was it? (raised-line, collage maps, etc.)
	Do you have: a smartphone, laptop, tablet, computer?
	Do you regularly use them? (1 = never, 5 = very often)*
	Do access a digital document, what type of device do you use?
	Do you regularly use them? (1 = never, 5 = very often)*
	How good are you at mentally representing space? [84] *
	Do you know what is Google Maps / Open street map? Has someone already describe to you how these interfaces work?
	Do you know what does zooming/panning/dragging mean?
Questionnaire 2: Comprehension	Do you think that you managed to understand the map? *
	During the test, did you experience the feeling of being lost, or of not knowing which part of the map you were exploring? *
	Between panning and zooming, which action makes it harder to understand the map, and why?
	How did you do to memorize the map? Did you use a particular strategy?
	(for the sliders only) Did the position of the sliders help you to understand which part of the map you were exploring?
Questionnaire 3: Interaction	When panning, did you manage to move the frame as efficiently as expected? *
	When zooming, did you manage to change the level of zoom as efficiently as expected? *
	Between panning and zooming, which action was the most difficult to perform?
Questionnaire 4: Overall usability and preferences	What are the features of the application that you preferred the most and the ones that were the most useful?
	What are the features of the application that you preferred the less and the ones that were the less useful?
	Do you think of other features that would be useful? Which ones?
	Between the Keyboard and the Sliders, which interaction technique is the most efficient to explore the map and why?
	Between the Keyboard and the Sliders, which interaction technique is the most pleasant to use and why?
	If you had access to the system and that only one interaction technique could be used, which one would you choose and why?

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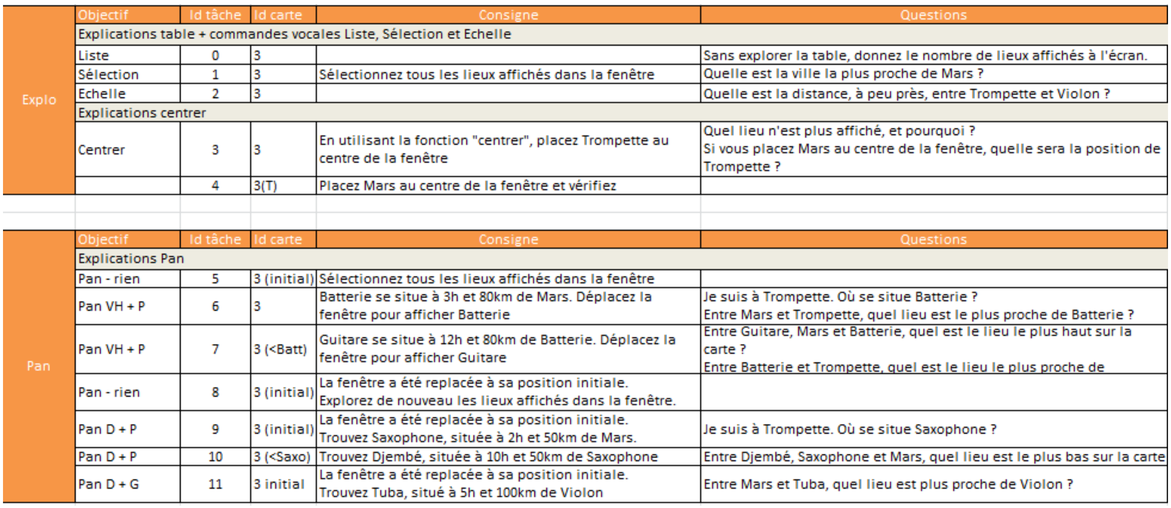
[84] In French : « Pensez-vous avoir de bonnes capacités à vous représenter l'espace mentalement ? »

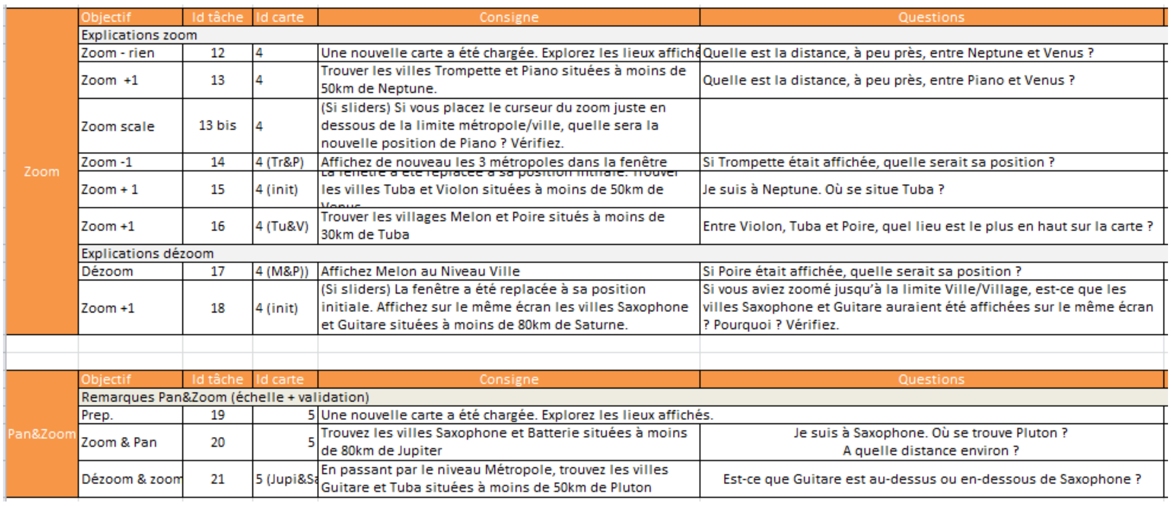
C.3. List of trials for training

SESSION 1



	Objectif	Id tâche	Id carte	Consigne	Questions
Explo	Explications table + commandes vocales Liste, Sélection et Echelle				
	Liste	0	3		Sans explorer la table, donnez le nombre de lieux affichés à l'écran.
	Sélection	1	3	Sélectionnez tous les lieux affichés dans la fenêtre	Quelle est la ville la plus proche de Mars ?
	Echelle	2	3		Quelle est la distance, à peu près, entre Trompette et Violon ?
	Explications centrer				
	Centrer	3	3	En utilisant la fonction "centrer", placez Trompette au centre de la fenêtre	Quel lieu n'est plus affiché, et pourquoi ? Si vous placez Mars au centre de la fenêtre, quelle sera la position de Trompette ?
		4	3(T)	Placez Mars au centre de la fenêtre et vérifiez	

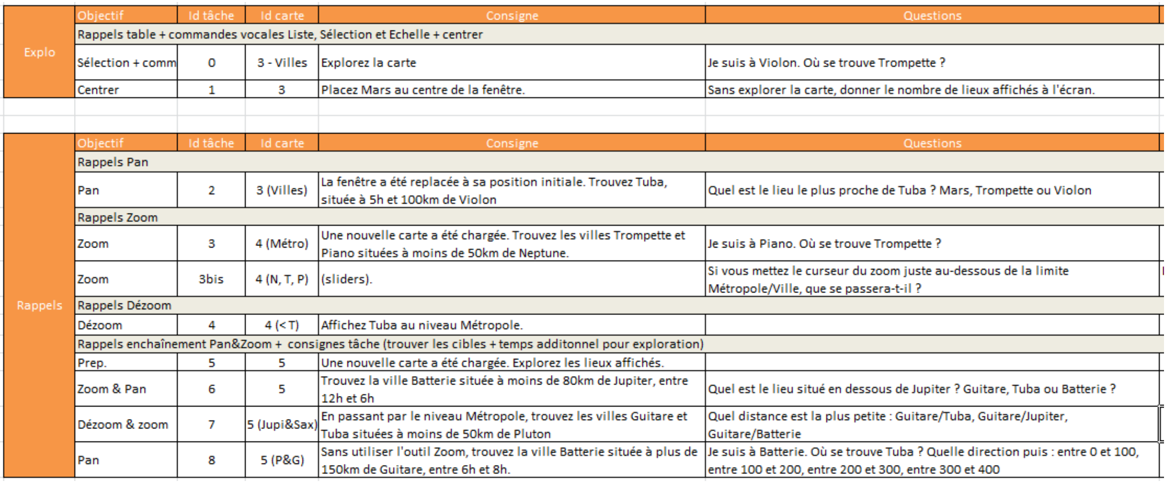
	Objectif	Id tâche	Id carte	Consigne	Questions
Pan	Explications Pan				
	Pan - rien	5	3 (initial)	Sélectionnez tous les lieux affichés dans la fenêtre	
	Pan VH + P	6	3	Batterie se situe à 3h et 80km de Mars. Déplacez la fenêtre pour afficher Batterie	Je suis à Trompette. Où se situe Batterie ? Entre Mars et Trompette, quel lieu est le plus proche de Batterie ?
	Pan VH + P	7	3 (<Batt)	Guitare se situe à 12h et 80km de Batterie. Déplacez la fenêtre pour afficher Guitare	Entre Guitare, Mars et Batterie, quel est le lieu le plus haut sur la carte ? Entre Batterie et Trompette, quel est le lieu le plus proche de
	Pan - rien	8	3 (initial)	La fenêtre a été replacée à sa position initiale. Explorez de nouveau les lieux affichés dans la fenêtre.	
	Pan D + P	9	3 (initial)	La fenêtre a été replacée à sa position initiale. Trouvez Saxophone, située à 2h et 50km de Mars.	Je suis à Trompette. Où se situe Saxophone ?
	Pan D + P	10	3 (<Saxo)	Trouvez Djembé, située à 10h et 50km de Saxophone	Entre Djembé, Saxophone et Mars, quel lieu est le plus bas sur la carte
	Pan D + G	11	3 initial	La fenêtre a été replacée à sa position initiale. Trouvez Tuba, situé à 5h et 100km de Violon	Entre Mars et Tuba, quel lieu est plus proche de Violon ?



	Objectif	Id tâche	Id carte	Consigne	Questions
Zoom	Explications zoom				
	Zoom - rien	12	4	Une nouvelle carte a été chargée. Explorez les lieux affiché	Quelle est la distance, à peu près, entre Neptune et Venus ?
	Zoom +1	13	4	Trouver les villes Trompette et Piano situées à moins de 50km de Neptune.	Quelle est la distance, à peu près, entre Piano et Venus ?
	Zoom scale	13 bis	4	(Si sliders) Si vous placez le curseur du zoom juste en dessous de la limite métropole/ville, quelle sera la nouvelle position de Piano ? Vérifiez.	
	Zoom -1	14	4 (Tr&P)	Affichez de nouveau les 3 métropoles dans la fenêtre	Si Trompette était affichée, quelle serait sa position ?
	Zoom + 1	15	4 (init)	La fenêtre a été replacée à sa position initiale. Trouver les villes Tuba et Violon situées à moins de 50km de Venus	Je suis à Neptune. Où se situe Tuba ?
	Zoom +1	16	4 (Tu&V)	Trouver les villages Melon et Poire situés à moins de 30km de Tuba	Entre Violon, Tuba et Poire, quel lieu est le plus en haut sur la carte ?
	Explications dézoom				
	Dézoom	17	4 (M&P))	Affichez Melon au Niveau Ville	Si Poire était affichée, quelle serait sa position ?
	Zoom +1	18	4 (init)	(Si sliders) La fenêtre a été replacée à sa position initiale. Affichez sur le même écran les villes Saxophone et Guitare situées à moins de 80km de Saturne.	Si vous aviez zoomé jusqu'à la limite Ville/Village, est-ce que les villes Saxophone et Guitare auraient été affichées sur le même écran ? Pourquoi ? Vérifiez.

	Objectif	Id tâche	Id carte	Consigne	Questions
Pan&Zoom	Remarques Pan&Zoom (échelle + validation)				
	Prep.	19	5	Une nouvelle carte a été chargée. Explorez les lieux affichés.	
	Zoom & Pan	20	5	Trouvez les villes Saxophone et Batterie situées à moins de 80km de Jupiter	Je suis à Saxophone. Où se trouve Pluton ? A quelle distance environ ?
	Dézoom & zoom	21	5 (Jupi&Sa	En passant par le niveau Métropole, trouvez les villes Guitare et Tuba situées à moins de 50km de Pluton	Est-ce que Guitare est au-dessus ou en-dessous de Saxophone ?

SESSION 2

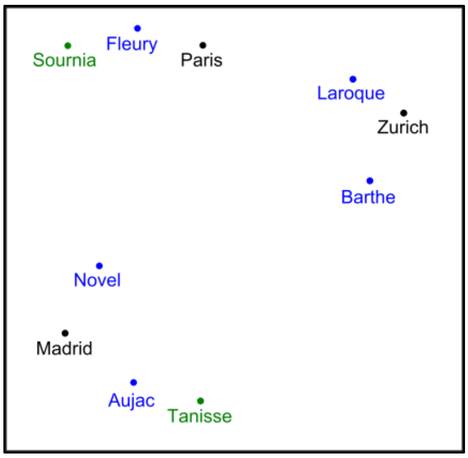


	Objectif	Id tâche	Id carte	Consigne	Questions
Explo	Rappels table + commandes vocales Liste, Sélection et Echelle + centrer				
	Sélection + comm	0	3 - Villes	Explorez la carte	Je suis à Violon. Où se trouve Trompette ?
	Centrer	1	3	Placez Mars au centre de la fenêtre.	Sans explorer la carte, donner le nombre de lieux affichés à l'écran.

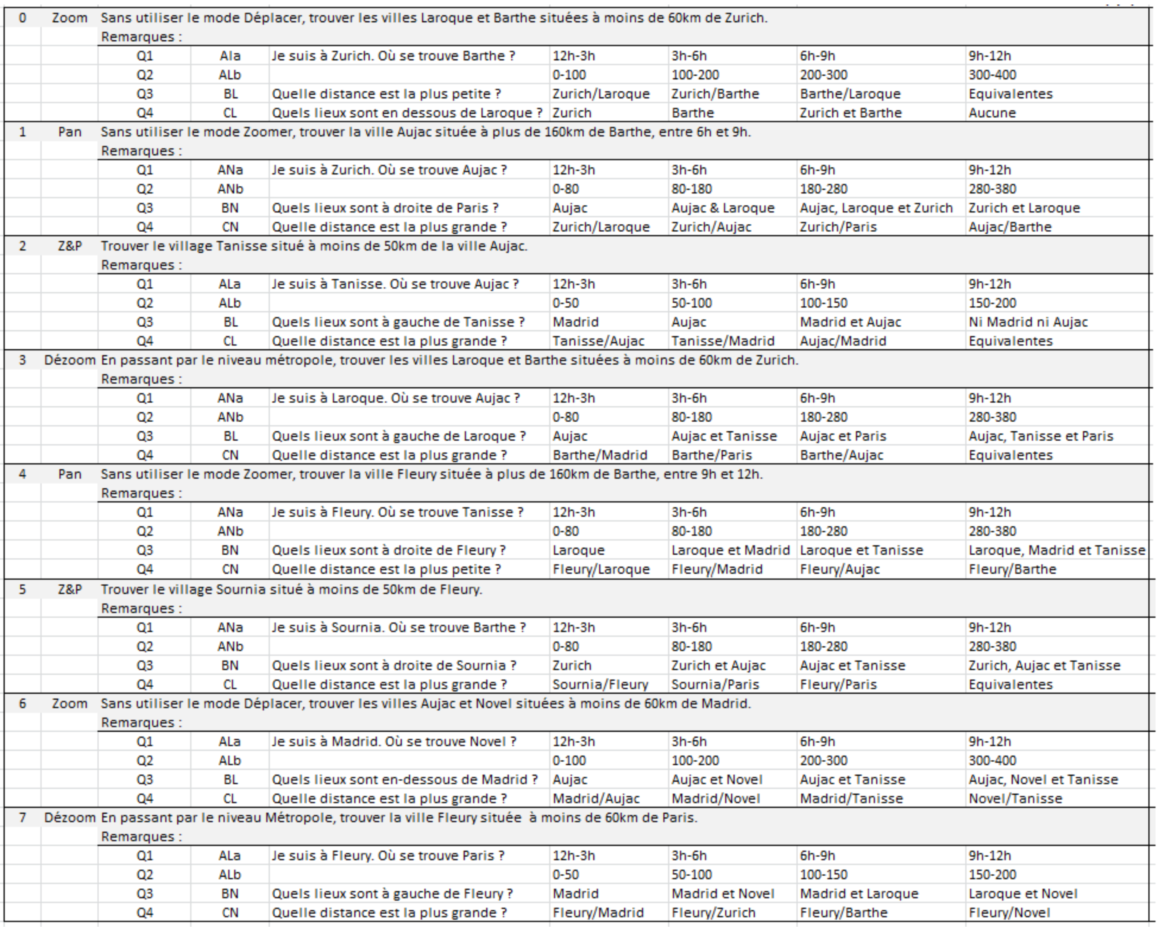
	Objectif	Id tâche	Id carte	Consigne	Questions
Rappels	Rappels Pan				
	Pan	2	3 (Villes)	La fenêtre a été replacée à sa position initiale. Trouvez Tuba, située à 5h et 100km de Violon	Quel est le lieu le plus proche de Tuba ? Mars, Trompette ou Violon
	Rappels Zoom				
	Zoom	3	4 (Métro)	Une nouvelle carte a été chargée. Trouvez les villes Trompette et Piano situées à moins de 50km de Neptune.	Je suis à Piano. Où se trouve Trompette ?
	Zoom	3bis	4 (N, T, P)	(sliders).	Si vous mettez le curseur du zoom juste au-dessous de la limite Métropole/Ville, que se passera-t-il ?
	Rappels Dézoom				
	Dézoom	4	4 (< T)	Affichez Tuba au niveau Métropole.	
	Rappels enchaînement Pan&Zoom + consignes tâche (trouver les cibles + temps additonnel pour exploration)				
	Prep.	5	5	Une nouvelle carte a été chargée. Explorez les lieux affichés.	
	Zoom & Pan	6	5	Trouvez la ville Batterie située à moins de 80km de Jupiter, entre 12h et 6h	Quel est le lieu situé en dessous de Jupiter ? Guitare, Tuba ou Batterie ?
	Dézoom & zoom	7	5 (Jupi&Sax)	En passant par le niveau Métropole, trouvez les villes Guitare et Tuba situées à moins de 50km de Pluton	Quel distance est la plus petite : Guitare/Tuba, Guitare/Jupiter, Guitare/Batterie
	Pan	8	5 (P&G)	Sans utiliser l'outil Zoom, trouvez la ville Batterie située à plus de 150km de Guitare, entre 6h et 8h.	Je suis à Batterie. Où se trouve Tuba ? Quelle direction puis : entre 0 et 100, entre 100 et 200, entre 200 et 300, entre 300 et 400

C.4. List of trials and questions for the test

MAP 1

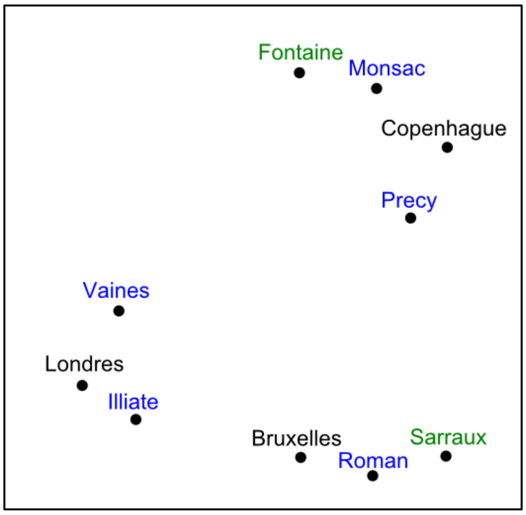


TRIALS AND QUESTIONS FOR MAP 1

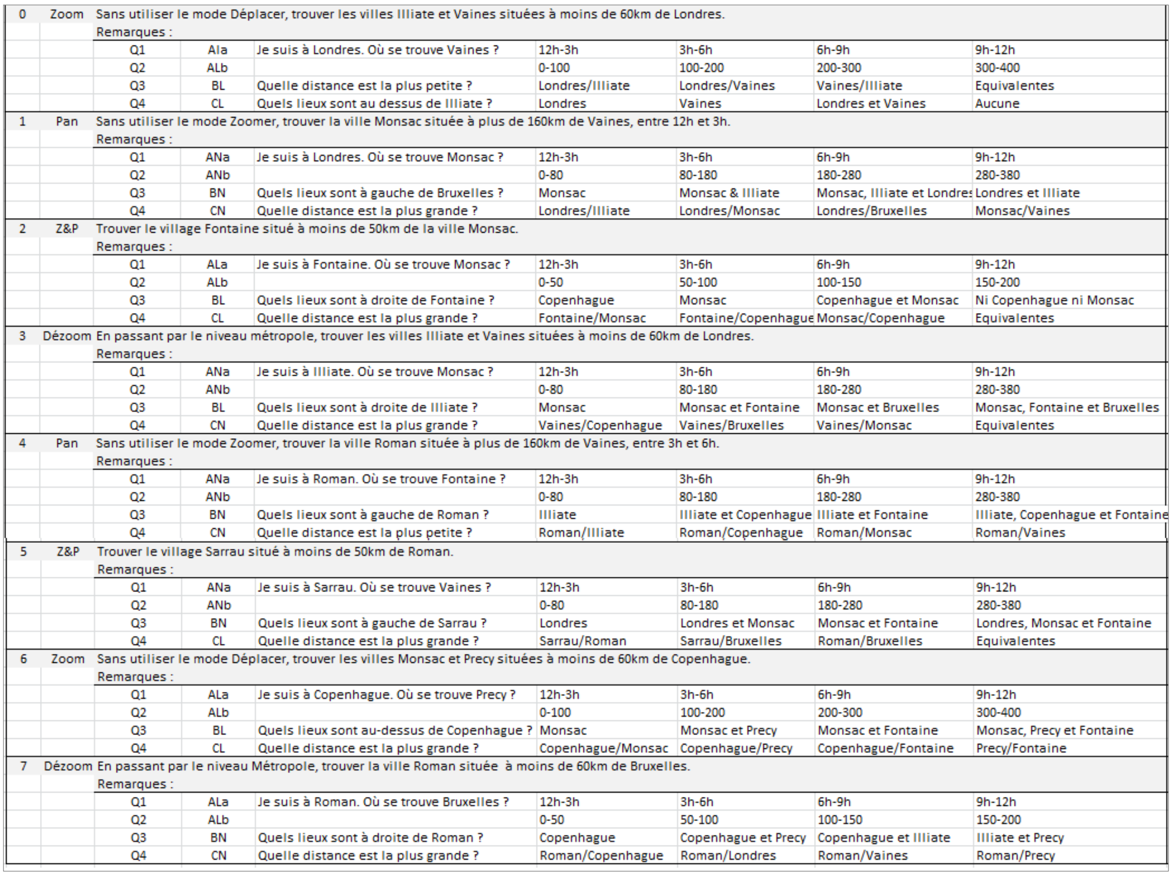


0	Zoom	Sans utiliser le mode Déplacer, trouver les villes Laroque et Barthe situées à moins de 60km de Zurich.					
		Remarques :					
		Q1	Ala	Je suis à Zurich. Où se trouve Barthe ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ALb		0-100	100-200	200-300	300-400
		Q3	BL	Quelle distance est la plus petite ?	Zurich/Laroque	Zurich/Barthe	Barthe/Laroque	Equivalentes
		Q4	CL	Quels lieux sont en dessous de Laroque ?	Zurich	Barthe	Zurich et Barthe	Aucune
1	Pan	Sans utiliser le mode Zoomer, trouver la ville Aujac située à plus de 160km de Barthe, entre 6h et 9h.					
		Remarques :					
		Q1	ANa	Je suis à Zurich. Où se trouve Aujac ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ANb		0-80	80-180	180-280	280-380
		Q3	BN	Quels lieux sont à droite de Paris ?	Aujac	Aujac & Laroque	Aujac, Laroque et Zurich	Zurich et Laroque
		Q4	CN	Quelle distance est la plus grande ?	Zurich/Laroque	Zurich/Aujac	Zurich/Paris	Aujac/Barthe
2	Z&P	Trouver le village Tanisse situé à moins de 50km de la ville Aujac.					
		Remarques :					
		Q1	ALa	Je suis à Tanisse. Où se trouve Aujac ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ALb		0-50	50-100	100-150	150-200
		Q3	BL	Quels lieux sont à gauche de Tanisse ?	Madrid	Aujac	Madrid et Aujac	Ni Madrid ni Aujac
		Q4	CL	Quelle distance est la plus grande ?	Tanisse/Aujac	Tanisse/Madrid	Aujac/Madrid	Equivalentes
3	Dézoom	En passant par le niveau métropole, trouver les villes Laroque et Barthe situées à moins de 60km de Zurich.					
		Remarques :					
		Q1	ANa	Je suis à Laroque. Où se trouve Aujac ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ANb		0-80	80-180	180-280	280-380
		Q3	BL	Quels lieux sont à gauche de Laroque ?	Aujac	Aujac et Tanisse	Aujac et Paris	Aujac, Tanisse et Paris
		Q4	CN	Quelle distance est la plus grande ?	Barthe/Madrid	Barthe/Paris	Barthe/Aujac	Equivalentes
4	Pan	Sans utiliser le mode Zoomer, trouver la ville Fleury située à plus de 160km de Barthe, entre 9h et 12h.					
		Remarques :					
		Q1	ANa	Je suis à Fleury. Où se trouve Tanisse ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ANb		0-80	80-180	180-280	280-380
		Q3	BN	Quels lieux sont à droite de Fleury ?	Laroque	Laroque et Madrid	Laroque et Tanisse	Laroque, Madrid et Tanisse
		Q4	CN	Quelle distance est la plus petite ?	Fleury/Laroque	Fleury/Madrid	Fleury/Aujac	Fleury/Barthe
5	Z&P	Trouver le village Sournia situé à moins de 50km de Fleury.					
		Remarques :					
		Q1	ANa	Je suis à Sournia. Où se trouve Barthe ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ANb		0-80	80-180	180-280	280-380
		Q3	BN	Quels lieux sont à droite de Sournia ?	Zurich	Zurich et Aujac	Aujac et Tanisse	Zurich, Aujac et Tanisse
		Q4	CL	Quelle distance est la plus grande ?	Sournia/Fleury	Sournia/Paris	Fleury/Paris	Equivalentes
6	Zoom	Sans utiliser le mode Déplacer, trouver les villes Aujac et Novel situées à moins de 60km de Madrid.					
		Remarques :					
		Q1	ALa	Je suis à Madrid. Où se trouve Novel ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ALb		0-100	100-200	200-300	300-400
		Q3	BL	Quels lieux sont en-dessous de Madrid ?	Aujac	Aujac et Novel	Aujac et Tanisse	Aujac, Novel et Tanisse
		Q4	CL	Quelle distance est la plus grande ?	Madrid/Aujac	Madrid/Novel	Madrid/Tanisse	Novel/Tanisse
7	Dézoom	En passant par le niveau Métropole, trouver la ville Fleury située à moins de 60km de Paris.					
		Remarques :					
		Q1	ALa	Je suis à Fleury. Où se trouve Paris ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ALb		0-50	50-100	100-150	150-200
		Q3	BN	Quels lieux sont à gauche de Fleury ?	Madrid	Madrid et Novel	Madrid et Laroque	Laroque et Novel
		Q4	CN	Quelle distance est la plus grande ?	Fleury/Madrid	Fleury/Zurich	Fleury/Barthe	Fleury/Novel

MAP 2



TRIALS AND QUESTIONS FOR MAP 2



0	Zoom	Sans utiliser le mode Déplacer, trouver les villes Illiate et Vaines situées à moins de 60km de Londres.						
		Remarques :						
		Q1	ALa	Je suis à Londres. Où se trouve Vaines ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ALb		0-100	100-200	200-300	300-400
		Q3	BL	Quelle distance est la plus petite ?	Londres/Illiate	Londres/Vaines	Vaines/Illiate	Equivalentes
		Q4	CL	Quels lieux sont au dessus de Illiate ?	Londres	Vaines	Londres et Vaines	Aucune
1	Pan	Sans utiliser le mode Zoomer, trouver la ville Monsac située à plus de 160km de Vaines, entre 12h et 3h.						
		Remarques :						
		Q1	ANa	Je suis à Londres. Où se trouve Monsac ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ANb		0-80	80-180	180-280	280-380
		Q3	BN	Quels lieux sont à gauche de Bruxelles ?	Monsac	Monsac & Illiate	Monsac, Illiate et Londres	Londres et Illiate
		Q4	CN	Quelle distance est la plus grande ?	Londres/Illiate	Londres/Monsac	Londres/Bruxelles	Monsac/Vaines
2	Z&P	Trouver le village Fontaine situé à moins de 50km de la ville Monsac.						
		Remarques :						
		Q1	ALa	Je suis à Fontaine. Où se trouve Monsac ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ALb		0-50	50-100	100-150	150-200
		Q3	BL	Quels lieux sont à droite de Fontaine ?	Copenhague	Monsac	Copenhague et Monsac	Ni Copenhague ni Monsac
		Q4	CL	Quelle distance est la plus grande ?	Fontaine/Monsac	Fontaine/Copenhague	Monsac/Copenhague	Equivalentes
3	Dézoom	En passant par le niveau métropole, trouver les villes Illiate et Vaines situées à moins de 60km de Londres.						
		Remarques :						
		Q1	ANa	Je suis à Illiate. Où se trouve Monsac ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ANb		0-80	80-180	180-280	280-380
		Q3	BL	Quels lieux sont à droite de Illiate ?	Monsac	Monsac et Fontaine	Monsac et Bruxelles	Monsac, Fontaine et Bruxelles
		Q4	CN	Quelle distance est la plus grande ?	Vaines/Copenhague	Vaines/Bruxelles	Vaines/Monsac	Equivalentes
4	Pan	Sans utiliser le mode Zoomer, trouver la ville Roman située à plus de 160km de Vaines, entre 3h et 6h.						
		Remarques :						
		Q1	ANa	Je suis à Roman. Où se trouve Fontaine ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ANb		0-80	80-180	180-280	280-380
		Q3	BN	Quels lieux sont à gauche de Roman ?	Illiate	Illiate et Copenhague	Illiate et Fontaine	Illiate, Copenhague et Fontaine
		Q4	CN	Quelle distance est la plus petite ?	Roman/Illiate	Roman/Copenhague	Roman/Monsac	Roman/Vaines
5	Z&P	Trouver le village Sarrau situé à moins de 50km de Roman.						
		Remarques :						
		Q1	ANa	Je suis à Sarrau. Où se trouve Vaines ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ANb		0-80	80-180	180-280	280-380
		Q3	BN	Quels lieux sont à gauche de Sarrau ?	Londres	Londres et Monsac	Monsac et Fontaine	Londres, Monsac et Fontaine
		Q4	CL	Quelle distance est la plus grande ?	Sarrau/Roman	Sarrau/Bruxelles	Roman/Bruxelles	Equivalentes
6	Zoom	Sans utiliser le mode Déplacer, trouver les villes Monsac et Precy situées à moins de 60km de Copenhague.						
		Remarques :						
		Q1	ALa	Je suis à Copenhague. Où se trouve Precy ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ALb		0-100	100-200	200-300	300-400
		Q3	BL	Quels lieux sont au-dessus de Copenhague ?	Monsac	Monsac et Precy	Monsac et Fontaine	Monsac, Precy et Fontaine
		Q4	CL	Quelle distance est la plus grande ?	Copenhague/Monsac	Copenhague/Precy	Copenhague/Fontaine	Precy/Fontaine
7	Dézoom	En passant par le niveau Métropole, trouver la ville Roman située à moins de 60km de Bruxelles.						
		Remarques :						
		Q1	ALa	Je suis à Roman. Où se trouve Bruxelles ?	12h-3h	3h-6h	6h-9h	9h-12h
		Q2	ALb		0-50	50-100	100-150	150-200
		Q3	BN	Quels lieux sont à droite de Roman ?	Copenhague	Copenhague et Precy	Copenhague et Illiate	Illiate et Precy
		Q4	CN	Quelle distance est la plus grande ?	Roman/Copenhague	Roman/Londres	Roman/Vaines	Roman/Precy

APPENDIX D
WORK IN PROGRESS: DESIGNING SMALL AND STABLE OBJECTS

D.1. Motivations

With visual TUIs, there is rarely a need to use a large number of tangible objects as most elements of the representation can be visually displayed. However, having the opportunity to use several tangible objects is essential to increase the complexity of tabletop tangible maps and diagrams for visually impaired users. In addition, to avoid physical clutter, the objects should be relatively small and, as we already discussed, they should also be stable. In Chapter 2, Part D, 3.1, we reviewed the main approaches that exist to track tangible objects. We saw that solutions based on camera placed below the surface led to tangible objects whose size is most often superior to four centimeters. Other alternatives are also limited. For example, it is possible to use a transparent glass surface, as we did for the Tangible Reels prototypes, but this prevents the use of visual feedback. The Microsoft Surface can track fingers and small objects (around 2 centimeters), based on several infrared cameras, but its development has been discontinued. Other tracking technologies require dedicated hardware (e.g. [334]) or are sensitive to lighting conditions (e.g. [341]). There is therefore a need to develop small tangible objects (less than or equal to two centimeters) that can be tracked by an interactive table regardless of the lighting conditions and without using a camera placed above the tabletop.

D.2. Related work

A recurrent idea to ease the tracking of objects is to use “footprints” instead of fiducials. Footprints are composed of a limited number of blobs, whose configurations encode one unique ID. For example, we already described TouchTokens [210], which are tangible objects whose shape constrain how users can grasp them. By detecting the positions of the fingers that hold the object, the system is able to identify which object is being manipulated. These approaches have mainly been used for capacitive touchscreens, but can also be adapted to interactive surfaces composed of IR cameras. For example, TouchBugs [217] are small objects that embed two LEDs, which are detected by a camera placed under the surface: the frequency and amplitude of the light signal allow the application to detect the objects as well as their position and orientation.

D.3. Description of the prototype

Building on TouchBugs [217], we aim to develop a set of small and stable tangible objects that would be compliant with two interactive tables available in the IRIT laboratory, and that cannot be used to track small objects: a MultiTaction table, which includes several IR cameras; an Immersion table, which is composed of one IR camera placed under the projection surface. A first step in making such tangible objects has been carried out by Paul Mesnigrente during his internship, under the supervision of Marc Macé and myself, and in collaboration with SphereL, a company specialized in the design and implementation of technological solutions.

SphereL provided a set of objects composed of four LEDs whose blinking configurations differ from each object. Each object is also composed of an accelerometer. Both the LEDs and the accelerometer are controlled by a microcontroller. Using a sequence of video processing algorithms, and notably thresholding, it is possible to isolate the bright spots corresponding to each LED being turned on. When the tangible object is being moved (the movement being detected by the accelerometer), all LEDs are turned on and both the position and orientation of the object can be accurately computed. Otherwise, the LEDs only blink with moderate frequency, which reduce the amount of power required.

Each object is identified by a unique ID, which is a sequence of eight bits. The following algorithm was proposed: each LED is associated with a number (from one to four), which corresponds to the position of one bit among four. Two frames are subsequently analyzed, and each frame encodes four bits, as shown in Figure D. 1 (LED on = 1; LED off = 0). By combining these two pieces of information, the ID of the object can be computed (e.g. 1100 1011 = 203). Because the configuration of the LEDs is asymmetric, it is possible to identify each LED by computing the distances and angles between them, and, when they are all turned on, to determine the orientation of the object.

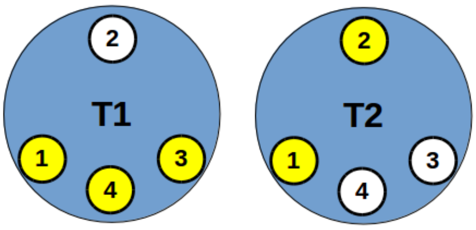


Figure D. 1. Each object is composed of four LEDs. The first frame gives the first part of the ID (here, 1011). Right: the second frame gives the second part of the ID (here, 1100). By combining the two parts, the ID can be computed (1100 1011 = 203).

A second step was carried out by Ludovic Lesur as part of his engineer internship, under the supervision of Marc Macé and myself as well. The objective was to reduce the size of the objects (initially with a diameter of around five centimeters), so that they could be embedded into a small cylinder, whose lower part would be filled with lead to make them stable. A first proof-of-concept prototype was developed, which included three LEDs only (to reduce its size), as shown in Figure D. 2. Further development are required to make this proof-of-concept prototype compliant with the application developed by Paul Mesnigrente, and to later embed them into cylinders filled with lead.

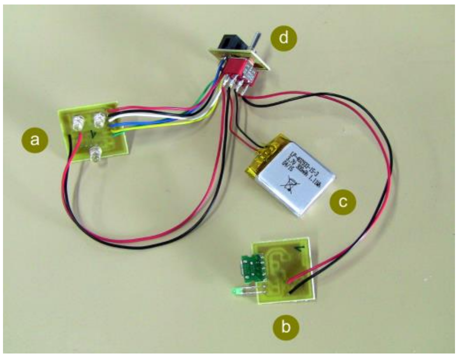


Figure D. 2. Current version of the prototype. Each object is composed of: a) one PCB with one microcontroller, three LEDS and one accelerometer; b) one load circuit with one micro USB port to charge the battery; c) one battery; d) one module with one switch.

APPENDIX E
SCENARIOS FOR THE CELLULO PROJECT

The following table describes a number of collaborative scenarios that have been designed and that rely on the use of Cellulos [223] (see Chapter 6, 4.2):

Scenario	Version	Description
Where I am? - Where are you?	1	Student A stays at a particular place (e.g. near the door). The robot on the plan moves to the corresponding position. Student B, who is reading the plan, can relate the position of the robot on the plan with the position of A in the classroom, so as to better understand changes of scale and perspective between the map and the real environment.
	2	A moves while B is following the robot representing A's position. B must then describe the trajectory of A (e.g. "you moved from the door to the table"), who can confirm whether the description is correct or not.
	3	A stays at a particular place and indicates to B, who is reading the plan, where she/he is. The robot moves to a correct or incorrect position. Based on the indications given by A, B must decide whether or not the robot is correctly placed. Inversely, the robot can always move to its correct position but A can give false indications: in that case, B must indicate whether A is lying or not.
Scavenger hunt	1	Physical treasures are hidden in the classroom and their position is marked on the plan. B, who is reading the plan, must guide A towards the treasures using verbal indications. The position of the robot allows B to know where A is and to give indications accordingly (e.g. "go towards the door", "go left", etc.)
	2	Virtual treasures are hidden on the digital plan; their positions correspond to those of physical treasures hidden in the classroom. A must find the physical treasures and indicate to B where they are. B must move a particular robot above the map to locate the digital treasure (the robot vibrates whenever a treasure has been found).

APPENDIX F
RÉSUMÉ DÉTAILLÉ (FRANÇAIS)

Ce résumé reprend les principaux points de la thèse, à savoir le contexte et l'état de l'art (Chapitres 1 et 2), les contributions théoriques et empiriques de la thèse (Chapitres 3, 4 et 5), et la description d'un certain nombre de perspectives (Chapitre 6 et 7). Les sections consacrées aux évaluations donnent un aperçu de la méthodologie et des principaux résultats uniquement. Pour une description complète et des données précises, nous renvoyons le lecteur à la version complète de ce mémoire.

CHAPITRES 1 ET 2 – INTRODUCTION, ETAT DE L'ART ET QUESTIONS DE RECHERCHE

Les travaux présentés dans le chapitre 2 ont fait l'objet de trois publications :

- J. Ducasse, M. Macé, C. Jouffrais. *From open geographical data to tangible maps : improving the accessibility of maps for visually impaired people.* GeoVis'15. Papier long.
- J. Ducasse, A. Brock, C. Jouffrais. *Accessible Interactive Maps for Visually Impaired Users.* In: Pissaloux E., Velazquez R. (eds). Mobility of Visually Impaired People. Springer. 2008. Book chapter.
- J. Ducasse, B. Oriola, M. Macé, C. Jouffrais. *Concevoir des interfaces tangibles et spatiales pour des utilisateurs déficients visuels : pourquoi et comment ?* Papier long.

Rendre accessible les cartes et diagrammes : pourquoi ? (Chapter 1, 2 et Chapter 2, Part A)
Les représentations graphiques jouent un rôle essentiel dans nos vies personnelles et professionnelles. Dans cette thèse, nous nous sommes intéressés à deux grandes catégories de représentations graphiques : les cartes géographiques et les diagrammes (e.g. histogrammes, schémas, organigrammes, arbres généalogiques, etc.). Ces représentations graphiques peuvent être utilisées pour réaliser un grand nombre de tâches, telles que se repérer, explorer des données statistiques, résoudre des problèmes, présenter des données, etc. Bien que ces représentations soient majoritairement destinées à des personnes voyantes (car elles sont visuelles), de nombreuses études ont démontré que les personnes déficientes visuelles peuvent aussi tirer parti de ces sources d'informations.

Rendre accessible les cartes et diagrammes : comment ?

Supports tactiles non-interactifs (Chapter 2, Part B)
Pour rendre des cartes et des diagrammes visuels accessibles à des personnes déficientes visuelles, plusieurs solutions existent. Parmi les solutions traditionnelles, on peut distinguer deux types de support : les supports tactiles statiques (Chapter 2, Part B, 3.1), et les supports tactiles reconfigurables (Chapter 2, Part B, 3.2). Les supports statiques consistent le plus souvent en une feuille de papier spécial sur laquelle un graphique dont le contenu a été adapté (et simplifié) est imprimé. La feuille est ensuite passée dans un four et, sous l'effet de la chaleur, les microcapsules de polystyrène contenues dans le papier gonflent et éclatent, créant ainsi un relief qu'une personne déficiente visuelle peut toucher. D'autres méthodes de production existent (impression

3D par exemple), et résultent elles aussi en un support tactile (i.e. en relief) qui ne peut être édité. Dans les centres d'éducation spécialisés, d'autres techniques sont utilisées, qui résultent en des graphiques tactiles pouvant être édités : ces graphiques peuvent être construits avec des aimants sur un tableau aimanté (e.g. pour représenter un itinéraire) ou avec des punaises insérées dans un tableau de liège et reliées entre elles par des élastiques (e.g. pour représenter des formes géométriques). Un autre support est couramment utilisé : il s'agit d'une feuille de papier spécialisé (papier « allemand ») que l'on pose sur une planche de dessin et sur laquelle on écrit avec un stylo standard : au contact du stylo, la feuille se plisse et crée un relief que l'utilisateur peut toucher.

Qu'ils soient statiques ou reconfigurables, ces supports tactiles souffrent de deux défauts majeurs (Chapter 2, Part B, 3.3 et Chapter 2, Part B, 4). D'une part, seul un nombre limité d'informations peut être présenté ; ceci est dû au matériel utilisé, aux contraintes imposées par l'exploration tactile d'un document (le « champ de toucher » est limité par rapport au champ de vision et l'acuité tactile est inférieure à l'acuité visuelle), et à l'utilisation de libellés écrits en Braille, qui prennent beaucoup de place. D'autre part, ces supports ne sont pas interactifs : par conséquent, il n'est pas possible de modifier ou sélectionner les informations associées à un élément du graphique, et, dans le cas des supports reconfigurables, les élèves sont dépendants d'une personne voyante pour placer les objets au bon endroit, ce qui réduit considérablement leur autonomie. Le manque d'interactivité contraint aussi le type de tâches qui peuvent être réalisées avec la carte ou le diagramme : il n'est par exemple pas possible de sélectionner quelles informations afficher, de changer d'échelle, etc.

Dispositifs interactifs (Chapter 2, Part C)
Une seconde approche, plus récente et encore souvent cantonnée aux laboratoires de recherche, consiste à développer des dispositifs interactifs, principalement basés sur l'utilisation de retours sonores. Dans cette thèse (Chapter 2, Part C, 2), nous avons proposé une nouvelle classification des dispositifs de cartes et diagrammes interactifs pour les personnes déficientes visuelles (il s'agit d'une extension d'une classification proposée en collaboration avec Anke Brock pour les cartes interactives uniquement). Nous faisons la distinction entre les cartes et diagrammes numériques (*digital)*, et les cartes et diagrammes hybrides (*hybrid*). Les premiers peuvent être affichés sur un écran ou projetés sur une surface plane (Chapter 2, Part C, 3). Ils peuvent être explorés en déplaçant un curseur sur les différents éléments qui les composent : en fonction de ce qui est affiché sous le curseur, des informations, principalement sonores, sont données par le système. Un graphique numérique peut être exploré par : des dispositifs d'entrée classiques (clavier, joystick, objet tangible) ; des dispositifs d'entrée augmentés, qui fournissent un retour de force (souris, manette de jeu, joystick) ou un retour tactile (par exemple une souris sur laquelle deux cellules Braille dynamiques sont fixées) ; un des doigts de l'utilisateur, détecté par une tablette ou une caméra.

Les cartes et diagrammes hybrides sont composés d'une représentation physique et d'une représentation numérique associée (Chapter 2, Part C, 4). Trois grandes catégories existent : les cartes et diagrammes tactiles interactifs (l'utilisateur peut interagir avec un support tactile classique posé sur une tablette, en effectuant par exemple des « taps » ou des « double-taps ») ; les cartes et diagrammes tangibles (composés de plusieurs objets physiques qui représentent des éléments, tels qu'une ville sur une carte ou un point sur un graphe) ; les cartes et diagrammes tactiles dynamiques (qui consistent généralement en des « tablettes Braille », composées d'une matrice de picots dont la hauteur peut varier).

Nous avons proposé une analyse détaillée de ces catégories de dispositifs, selon quatre dimensions (Chapter 2, Part C, 3.4 et Chapter 2, Part C, 4.4) : leur coût et leur disponibilité, leurs avantages et inconvénients en terme d'exploration (et de compréhension) ; leur contenu ; leur degré de modification. Le principal défaut des cartes et diagrammes numériques est qu'ils contraignent généralement l'exploration à un seul point de contact (c'est-à-dire que l'utilisateur peut accéder à une seule information à la fois, celle présente sous le curseur). Or, de nombreuses études ont montré que la possibilité d'explorer un graphique avec plusieurs doigts (i.e. avec plusieurs points de contacts) offre de nombreux avantages : cela rend l'exploration moins séquentielle, facilite la recherche d'éléments saillants, mais aussi l'encodage en mémoire des positions des éléments les uns par rapport aux autres et la comparaison de deux éléments (Chapter 2, Part B, 5.2). A ce titre, les cartes et diagrammes hybrides semblent plus pertinents, car ils peuvent être explorés avec les deux mains. Cependant, leur principal défaut est le fait qu'ils ne peuvent être modifiés (c'est le cas des cartes et diagrammes tactiles), ou bien s'ils peuvent être modifiés, qu'ils nécessitent des technologies dont le coût est prohibitif (une tablette Braille contenant 7000 picots coûte environ 50 000€). Les cartes et diagrammes tangibles offrent un compromis intéressant : non seulement ces graphiques peuvent être explorés à deux mains (car ils reposent sur un ensemble d'objets), mais ils peuvent aussi être modifiés (en manipulant les objets), tout en restant abordables (une caméra, une surface transparente et un ordinateur peuvent suffire). Cependant, à ce jour, peu de travaux ont été réalisés sur la conception, le développement et l'évaluation d'interfaces tangibles pour des personnes déficientes visuelles.

Cartes et diagrammes tangibles (Chapter 2, Part D et Chapter 2, Part E)
Les interfaces tangibles peuvent être définies comme des interfaces qui utilisent des objets physiques pour représenter ou contrôler des informations numériques. Elles sont donc composées d'une représentation physique (les objets), étroitement couplée à une représentation numérique (par exemple, une carte). Dans cette thèse, nous nous sommes plus précisément concentrés sur les Interfaces Tangibles sur Table (ITTs), et sur les ITTs *animées*, qui sont composées d'un ensemble d'objets dont la hauteur, forme ou position peut être modifiée par le système (il s'agit souvent d'objets motorisés). (Pour une synthèse des principales caractéristiques et modèles théoriques des interfaces tangibles et une présentation des technologies disponibles pour développer des ITTs, voir la partie D du Chapitre 2.)

Une des principales spécificités des ITTs destinées à des personnes déficientes visuelles concerne la nature des représentations : dans les ITTs visuelles, seule une partie de la représentation numérique est matérialisée (*embodied)* par la représentation physique, et des images ou des vidéos sont projetées sur la surface pour enrichir l'information présentée de manière tangible. En l'absence de retour visuel, la représentation numérique doit être entièrement matérialisée par des objets et du son, ce qui contraint fortement le type de représentations pouvant être rendues accessibles. Un autre aspect important concerne la conception des objets, qui doivent être stables afin de ne pas être renversés lors de l'exploration du graphique. Nous avons recensé et décrit deux prototypes de cartes tangibles accessibles et six prototypes de diagrammes tangibles accessibles, que nous avons ensuite analysé selon quatre axes : la nature des informations représentées, les propriétés des objets tangibles, l'interactivité des systèmes, leur disponibilité (Chapter 2, Part E, 3 et Chapter 2, Part E, 4). Cette analyse a montré que très peu de prototypes ont été formellement évalués par des personnes déficientes visuelles, et que peu de prototypes ont été développés. Aussi, les dispositifs permettaient de rendre accessibles uniquement un type précis de représentation graphique (e.g. un itinéraire ou un histogramme), et dont le contenu était très simple. Par ailleurs, aucune technique d'interaction pour la reconstruction d'une carte ou d'un diagramme n'a été proposée, et les techniques d'interaction proposées pour l'édition ou l'exploration des représentations graphiques n'ont pas toujours été évaluées. De manière générale, cette analyse a mis en évidence un manque de connaissances théoriques et empiriques sur l'utilisation de l'interaction tangible pour rendre accessibles des cartes et des diagrammes.

Enoncé de thèse et questions de recherche (Chapter 1, 3 et Chapter 1, 5)
L'objectif de cette thèse était d'étudier dans quelle mesure les ITTs (animées ou non) peuvent permettre à des personnes déficientes visuelles d'accéder de manière autonome à des représentations graphiques interactives, physiques et reconfigurables. Plus particulièrement, nous avons cherché à répondre aux questions suivantes : 1) quels sont les avantages et inconvénients des ITTs par rapport aux pratiques actuelles et aux projets de recherche existants ? ; 2) comment concevoir et développer des cartes et diagrammes tangibles pour des personnes déficientes visuelles ? ; 3) en prenant en compte les limitations inhérentes aux ITTs et les spécificités des ITTs pour les personnes déficientes visuelles, quelles représentations graphiques peuvent être rendues accessibles, et quelles tâches peuvent être supportées ? Pour répondre à ces questions, nous avons développé deux ITTs non-animées (les Tangible Reels et la Tangible Box), et une ITT animée (BotMap).

CHAPITRE 3 – TANGIBLE REELS : CONSTRUCTION ET EXPLORATION DE CARTES ET DE DIAGRAMMES TANGIBLES

Les travaux présentés dans ce chapitre ont fait l'objet de deux publications :

- J. Ducasse, M. Macé, M. Serrano, C. Jouffrais. *Tangible Reels: construction and exploration of tangible maps by visually impaired users*. CHI'16, 2186 – 2197. Papier long.
- J. Ducasse, M. Macé, M. Serrano, C. Jouffrais. *Tangible maps for visually impaired users: shape-changing perspectives*. CHI'16. Papier court (workshop).

Motivations (Chapter 3, 1)
L'objectif de ce projet était d'étudier dans quelle mesure l'interaction tangible peut permettre à une personne déficiente visuelle d'accéder de manière autonome à une carte physique et reconfigurable. Etant donné le faible nombre de travaux de recherche concernant les interfaces tangibles pour les non-voyants, nous nous sommes inspirés des pratiques actuelles (et notamment de la technique des aimants), et avons cherché à pallier leurs limitations (manque d'interactivité, représentations très simples, présence d'une personne voyante nécessaire). Le principe général du dispositif que nous avons conçu est le suivant : les utilisateurs sont guidés pour progressivement construire une carte à partir d'un ensemble d'objets tangibles ; une fois la carte reconstruite, ils peuvent l'explorer de manière interactive, et éventuellement l'éditer.

Conception des Tangible Reels (Chapter 3, 2)
Nous avons identifié cinq critères à prendre en compte pour la conception des objets tangibles : 1) les objets tangibles doivent permettre de matérialiser des symboles ponctuels (e.g. des villes) et linéaires (e.g. des rivières) ; 2) les objets tangibles doivent être détectables par le système de manière à fournir des retours sonores adéquats ; 3) chaque objet tangible doit être associé à un identifiant unique ; 4) les objets tangibles doivent être stables pendant l'exploration, tout en étant facile à manipuler pendant la phase de construction ; 5) les objets tangibles doivent être aussi petits que possible, de manière à maximiser le nombre d'objets pouvant être utilisés simultanément.

Afin de répondre à ces critères, plusieurs choix de conception ont été arrêtés. Premièrement, nous avons opté pour la bibliothèque TopCodes, qui permet de détecter et d'identifier des marqueurs circulaires de petite taille (environ deux centimètres de diamètre) sur un flux vidéo. Deuxièmement, afin de pouvoir matérialiser des lignes, nous avons choisi d'utiliser des badges rétractables composés d'une bobine et d'un câble de trente centimètres de longueur. Attachés aux objets tangibles, ces badges rétractables permettent à l'utilisateur de construire des lignes de différentes longueurs en reliant deux objets entre eux. Pour assurer la stabilité des objets, de nombreuses solutions ont été testées. Nous avons finalement opté pour deux solutions distinctes : la première consiste à lester des cylindres en PVC avec du plomb ; la deuxième consiste à utiliser des ventouses qui peuvent être fixées à la table et que l'on peut facilement détacher lorsqu'il est nécessaire de déplacer les objets. Nous avons nommé le premier type d'objet les *Weights* (poids), et le second les *Sucker pads* (ventouses). Dans les deux cas, le badge rétractable est solidement fixé sur les objets. Finalement, afin de faciliter la construction des lignes, nous avons attaché à chaque extrémité de câble un aimant et nous avons fixé autour des objets une chaînette métallique. Pour construire une ligne, il suffit donc de rapprocher l'extrémité d'un câble d'un autre objet et ainsi de les « connecter ».

Evaluation préliminaire (Chapter 3, 3)
Une première évaluation a été conduite afin d'évaluer l'utilisabilité des Tangible Reels. L'objectif était de tester leur stabilité et leur facilité de manipulation, mais aussi d'évaluer si des cartes et des diagrammes construits avec des Tangible Reels pouvaient être compris par des personnes déficientes visuelles.

Matériel et méthodes (Chapter 3, 3.1 et Chapter 3, 3.2)
Nous avons recruté quatre personnes déficientes visuelles. L'évaluation était composée de deux sessions (une pour les Sucker pads, une pour les Weights). Chaque session était composée de deux tâches (exploration et construction). Pour chaque tâche, deux types de carte étaient utilisés : une carte relativement simple, composée de neuf objets tangibles, et une carte plus complexe, composée de douze objets tangibles. Dans un premier temps, les sujets devaient explorer une carte construite par l'expérimentateur, puis la redessiner sur une feuille de papier « allemand » ou à l'aide d'aimants sur un tableau aimanté. Dans un second temps, les sujets devaient mémoriser une carte tactile puis la reconstruire sur la table avec les Tangible Reels, aussi précisément que possible.

Nous avons utilisé les mesures suivantes : le déplacement, en centimètres, de chaque objet tangible avant et après l'exploration d'une carte ; le nombre d'objets tangibles déplacés ou renversés lors de la tâche d'exploration ; un questionnaire composé de cinq affirmations que les sujets devaient évaluer sur une échelle de Likert de 1 à 7 ; le classement des deux types d'objet par ordre de préférence, pour l'exploration et la construction ; une note sur 10 évaluant la qualité des cartes dessinées. Pour cette dernière mesure, nous avons utilisé la méthode des juges : les cartes dessinées par les participants ont été présentées à quatre juges externes, qui devaient comparer leur similarité par rapport à la carte modèle, en leur attribuant une note variant de 0 à 10.

Résultats et discussion (Chapter 3, 3.3 et Chapter 3, 3.4)
Les résultats ont montré que les deux types d'objets étaient stables, même si les participants étaient plus enclins à renverser les Weights, notamment à cause de leur hauteur. Plus précisément, les réponses au questionnaire montrent que tous les participants ont trouvé que les Sucker pads étaient agréables à manipuler, alors que deux participants ont trouvé que les Weights étaient faciles à renverser. Pour l'exploration, tous les participants ont préféré les Sucker Pads. Pour la construction, deux participants ont préféré les Sucker Pads, et deux ont préféré les Weights. De manière générale, trois participants ont préféré les Sucker Pads. En ce qui concerne les cartes, les notes moyennes étaient de 8,1 (SD = 1,3) pour les cartes simples (7,6 pour les Weights ; 8,6 pour les Sucker Pads), et de 5,7 (SD = 2,7) pour les cartes plus complexes (6,1 pour les Weights ; 5.3 pour les Sucker Pads). En conclusion, cette évaluation préliminaire a montré que les deux types d'objets étaient stables et faciles à manipuler. Cependant, les participants étaient moins enclins à renverser les Sucker pads, qui ont été préférés par trois participants sur quatre. Pour la suite du projet, nous avons donc décidé de travailler avec les Sucker Pads uniquement.

Techniques d'interaction et feedback (Chapter 3, 4)

Construction (Chapter 3, 4.1)
L'utilisateur est guidé pas à pas pour placer les objets tangibles sur la table et les relier entre eux, afin de reconstruire la carte de manière progressive. Des instructions verbales sont données par le système pour indiquer à l'utilisateur de : 1) placer un nouvel objet sur la table ; 2) attacher un nouvel objet au dernier objet placé ; 3) attacher un nouvel objet à un objet déjà placé sur la table, mais qui n'est pas le dernier placé. Une fois qu'un nouvel objet est détecté par le système, des instructions de guidage sont données : si l'objet est situé loin de sa position finale, le système donne la distance et la direction à cette position (e.g. « 30 centimètres, 10 heures ») ; si l'objet est situé près de la cible, le système donne des indications plus fréquentes et détaillées (e.g. « haut, haut, droite, droite »). Lors de la construction, plusieurs messages sont donnés par le système pour indiquer à l'utilisateur qu'un objet est correctement placé, qu'une ligne a été construite, ou qu'un objet n'est plus détecté par le système (par exemple si l'utilisateur cache une partie du marqueur avec un de ses doigts).

Exploration (Chapter 3, 4.2)
Une fois que la carte est reconstruite, l'utilisateur peut interagir avec les objets tangibles et les lignes pour écouter leur nom. Pour cela, il doit pointer un objet ou une ligne avec un seul doigt, et rester en position pendant deux secondes environ. Le nom de l'objet ou de la ligne est alors donné.

Implémentation (Chapter 3, 5)
Une table en verre a été utilisée, sous laquelle se trouve une caméra reliée à un ordinateur. Les objets tangibles sont placés sur la table. Pour détecter la position des doigts de l'utilisateur (pour l'exploration), un cadre infrarouge a été placé sur la table, et légèrement surélevé, de façon à ce que le cadre détecte les doigts de l'utilisateur uniquement, et non les objets. L'application a été développée en Java et s'appuie sur la bibliothèque MT4J. Les informations en provenance du cadre infrarouge sont envoyées à l'application cliente MT4J grâce au protocole TUIO.

Evaluation : utilisabilité des techniques d'interaction (Chapter 3, 6)
L'objectif de cette évaluation était de mesurer l'utilisabilité des techniques d'interaction proposées (exploration et construction) et d'identifier le degré de complexité des cartes pouvant être reconstruites grâce aux Tangible Reels.

Matériel et méthodes (Chapter 3, 6.1 et Chapter 3, 6.2)
Nous avons recruté huit personnes déficientes visuelles. Après avoir appris à suivre les instructions de construction et la technique d'interaction pour l'exploration, les participants devaient reconstruire quatre cartes de complexité croissante (composées de 6, 8, 10 et 12 Tangible Reels). Une fois que les cartes étaient reconstruites, les participants devaient répondre à trois questions en explorant la carte (e.g. « quel est le nom des points situés aux extrémités de la ligne 2 ? »).

Nous avons utilisé les mesures suivantes : nombre de cartes correctement construites ; nombre de Tangible Reels correctement placés ; temps nécessaire pour construire une carte ; temps nécessaire pour placer un Tangible Reel ; taux de bonnes réponses aux questions ; temps nécessaire pour répondre à une question ; questionnaire SUS (utilisabilité) ; questionnaire NASA-TLX (charge mentale).

Résultats (Chapter 3, 6.3)

Construction (Chapter 3, 6.3.1)
Cinq Tangible Reels sur 288 ont été mal placés, sur cinq cartes différentes. Ainsi, 5 cartes sur 32 ont été incorrectement construites. Les erreurs étaient dues à des mauvaises manipulations des objets ou à une mauvaise interprétation des instructions. Les temps de complétion étaient d'environ 2 minutes pour la carte la plus simple, 3 minutes 30 pour les deux cartes intermédiaires, et 4 minutes 30 pour la carte la plus complexe. Le temps pour placer un Tangible Reel était similaire pour les quatre cartes, autour de 22,5 secondes (IC95 [18,6 ; 27,2]. Les deux étapes les plus longues étaient de suivre les instructions de guidage précises (environ 39% du temps nécessaire pour placer un Tangible Reel), ou les instructions pour attacher ou placer un nouvel objet (environ 49% du temps nécessaire pour placer un Tangible Reel). Il n'y avait pas de différences notables entre les cartes.

Exploration (Chapter 3, 6.3.2)
En ce qui concerne l'exploration, le taux de bonnes réponses était similaire entre les quatre cartes et variait entre 79% et 92%. Quatre types d'erreurs ont été observés : 1) les participants sélectionnaient une ligne en pointant une intersection, et le nom de l'autre ligne était donné ; 2) les cartes n'étaient pas correctement construites ; 3) les participants avaient des difficultés à réaliser le

geste de pointage correctement ; 4) il y avait un décalage entre la représentation physique et la représentation numérique. Le temps de complétion pour chaque question augmentait avec la complexité des cartes, et variait entre 10 et 30 secondes.

Questionnaires (Chapter 3, 6.3.3)
Seuls deux participants ont trouvé qu'il était difficile de construire les cartes les plus complexes. Dans tous les autres cas, les participants ont trouvé qu'il était facile ou « ni facile, ni difficile », de construire les cartes. Le score SUS était de 82,2 (IC95 [72,3 ; 90,6]). Le questionnaire NASA-TLX a montré que les participants ont trouvé que la tâche ne nécessitait pas une attention soutenue, et qu'ils étaient globalement très satisfaits de leur performance.

Discussion (Chapter 3, 6.4)
Les résultats montrent que le système permet à des personnes déficientes visuelles de reconstruire des cartes de manière autonome, et en un temps relativement court (moins de 5 minutes pour la carte la plus complexe). Les instructions ont été jugées très faciles à interpréter. Cependant, le temps nécessaire pour suivre les instructions de guidage précises suggère que le guidage pourrait être amélioré, même si la technique de guidage en deux temps s'est avérée satisfaisante. En ce qui concerne l'exploration, les résultats ont montré que bien que le système permettait aux utilisateurs d'écouter le nom des points et des lignes, il était parfois difficile pour les participants de sélectionner une ligne ou un objet en particulier (geste difficile à réaliser, et décalage entre les représentations physique et numérique). Nous avons montré que des cartes relativement complexes pouvaient être construites grâce aux Tangible Reels. Cependant, il ne semble pas souhaitable de construire des cartes davantage complexes : deux participants ont trouvé que la dernière carte était difficile à construire, et plusieurs participants ont indiqué qu'il devenait difficile de placer et manipuler les objets lorsque plusieurs objets étaient déjà placés sur la table. De manière générale, les utilisateurs ont été très satisfaits par le système et plusieurs d'entre eux ont indiqué que ce système serait particulièrement utile dans le cadre d'activités pédagogiques.

Atelier pédagogique (Chapter 3, 7)
Un atelier pédagogique a été mis en place en collaboration avec deux professeures de l'IJA et trois élèves (un très malvoyant, deux malvoyants). Trois améliorations ont été apportées au système pour cet atelier (Chapter 3, 7.1) : 1) développement d'une fonctionnalité permettant aux utilisateurs d'annoter la carte en associant à chaque ligne ou chaque objet des messages vocaux (un cube tangible doit être placé près de l'élément à annoter, et en fonction de la face présentée, l'enregistrement est lancé ou arrêté); 2) développement d'une fonctionnalité permettant aux utilisateurs de construire une carte ou un diagramme, puis d'enregistrer le graphique ainsi construit de manière à pouvoir le reconstruire ultérieurement grâce à des instructions de guidage ; 3) utilisation d'une homographie pour mieux faire coïncider le repère de la caméra (i.e. les coordonnées des objets) avec le repère du cadre infrarouge (i.e. les coordonnées des doigts de l'utilisateur).

Dans un premier temps, les élèves ont réalisé plusieurs exercices, allant du simple placement d'un objet à la construction de plusieurs lignes. Dans un second temps, les élèves ont réalisé plusieurs exercices portant sur la construction, l'exploration et l'annotation de la carte de France, symbolisée par six objets tangibles reliés entre eux et représentant six villes. Les observations réalisées ont montré le potentiel des Tangible Reels pour la conception d'activités pédagogiques variées et ludiques. La fonctionnalité permettant d'annoter les villes a particulièrement été appréciée par les professeures et les élèves. Les professeures ont également mentionné le fait que les trois élèves avaient été très engagés et concentrés tout au long de la séance, et ont aussi suggéré que les mouvements des bras liés à la construction de la carte pouvaient être très bénéfiques en termes d'apprentissage et de mémorisation.

Perspectives et discussion (Chapter 3, 8)
Une des principales limitations des Tangible Reels est leur taille. Cependant, l'utilisation de ventouses plus petites permettrait d'augmenter le nombre d'objets pouvant être utilisés simultanément, afin de construire des représentations plus complexes. D'autres solutions pourraient être envisagées, telles que le développement de techniques d'interaction pour rendre les aires de manière auditive, l'utilisation de « doubles badges » pour limiter le nombre d'objets devant être utilisés, et l'utilisation de petits objets qui pourraient dévier le trajet du câble pour construire des courbes. Enfin, le développement de Cord User Interfaces suggère que les cartes et diagrammes tangibles pourraient être augmentés par l'utilisation de cordes animées (et notamment vibrantes), par exemple pour représenter différents types de symboles linéaires (fleuves vs rues), ou pour attirer l'attention de l'utilisateur sur un élément linéaire en particulier.

Nous avons développé plusieurs techniques d'interaction pour l'exploration, la (re)construction et l'annotation de cartes tangibles par des utilisateurs déficients visuels, et nous avons formellement évalué les deux premières. Bien que plusieurs améliorations soient envisageables, l'utilisabilité du système est tout à fait satisfaisante et démontre le potentiel des interfaces tangibles pour rendre accessibles à des utilisateurs déficients visuels des cartes tangibles, de manière autonome. De manière générale, les Tangible Reels peuvent être utilisés non seulement pour reconstruire des cartes, mais aussi d'autres types de graphes (formes géométriques, histogrammes, organigrammes, etc.). Le système est adapté à une utilisation autonome, et s'est avéré particulièrement prometteur pour le développement d'activités pédagogiques basées sur la manipulation, la reconstruction et l'annotation de cartes et diagrammes.

CHAPITRE 4 – LA TANGIBLE BOX : GRAPHIQUES TANGIBLES ET TACTILES POUR DES ELEVES DEFICIENTS VISUELS

Les travaux présentés dans ce chapitre ont fait l'objet d'un article, en cours de soumission (TEI) :

- J. Ducasse, B. Oriola, M. Macé, C. Jouffrais. *The Tangible Box : tangible and tactile graphics for visually impaired students*. Papier long.

Motivations (Chapter 4, 1)
Suite à l'atelier pédagogique réalisé avec les Tangible Reels, nous avons souhaité explorer plus en détail comment les interfaces tangibles pourraient être utilisées au sein d'établissement scolaires spécialisés. Le système utilisé pour les Tangible Reels et les Tangible Reels eux-mêmes sont trop encombrants pour être utilisée de manière régulière dans un établissement spécialisé. Nous avons donc cherché à concevoir une interface peu encombrante qui répondrait aux critères suivants : être bas coût, facile à installer et à calibrer ; être suffisamment compacte pour pouvoir être transportée d'une classe à l'autre et pour pouvoir être stockée quelque part entre deux classes ; être adaptée à des élèves ayant des profils variés (âge, degré de cécité, niveau, etc.) ; pouvoir être

utilisée pour plusieurs matières et pour plusieurs activités, de façon à ce que les professeurs n'aient pas besoin d'avoir une interface pour chaque matière qu'ils enseignent.

Conception et fabrication de la Tangible Box (Chapter 4, 2 et Chapter 4, 3)

Conception des objets tangibles

Nous avons souhaité mettre à disposition des élèves des objets tangibles stables et de petite taille, dont la détection ne pourrait être empêchée par l'occlusion des objets par les mains de l'élève. Pour cela, les objets tangibles sont composés de deux parties, chaque partie contenant un aimant. La partie supérieure est placée sur la surface ; la partie inférieure est placée sous la surface. Les deux parties sont maintenues l'une contre l'autre grâce au champ magnétique des aimants. Un marqueur est accolé sous la partie inférieure de l'objet, et une caméra est placée sous la surface pour détecter le marqueur. Ainsi, lorsque l'utilisateur déplace la partie supérieure de l'objet, la partie inférieure se déplace de la même manière et la caméra détecte ce déplacement : on peut donc connaître à tout moment les déplacements de l'objet tangible. Afin d'éviter que les parties inférieures des objets tombent si les parties supérieures sont involontairement soulevées, une feuille magnétique est placée sous la surface.

Prise en compte de différentes matières, activités et profils d'élèves.

Afin que la Tangible Box puisse être utilisée pour différentes activités et élèves, nous avons choisi d'utiliser des supports tactiles habituellement utilisés par les professeurs et les élèves, et de les rendre interactifs grâce aux objets tangibles décrits précédemment. Ainsi, les supports tactiles peuvent présenter différents types de graphiques (graphes, frises chronologiques, cartes, etc.) et être adaptés au profil de l'élève (bigraphisme, degré de simplification des tracés, etc.). Comme les aimants contenus dans les objets sont relativement puissants, des supports de différentes épaisseurs peuvent être utilisés (un système de fixation permet de maintenir en place des supports de différentes épaisseurs, tailles et orientations). Jusqu'à présent, les supports suivants ont été testés : graphiques tactiles thermoformés et thermogonflés, fins graphiques imprimés en 3D ; graphiques découpés dans du bois ou du plexiglas ; feuilles Dycem et planche de dessin. Ainsi, la Tangible Box s'appuie sur les avantages des graphiques tactiles traditionnels (bigraphisme, quantité d'information présentée, etc.), tout en les rendant interactifs et reconfigurables. Par ailleurs, les objets tangibles ont été conçus de manière à être très génériques. Cependant, il est possible de les personnaliser en imprimant des coques en 3D de différentes formes, tailles, textures, etc. Ainsi, il est possible d'adapter les objets aux différentes activités, mais aussi au profil des élèves (par exemple, il est possible de concevoir un objet de manière à ce qu'il soit facile à manipuler par un élève ayant des problèmes de motricité fine).

Facilité d'installation et coût du dispositif

Finalement, afin de rendre le système peu cher, facile à transporter et à installer, nous avons opté pour l'utilisation d'un Raspberry Pi, ainsi que pour l'utilisation d'une caméra grand-angle (afin de réduire la hauteur du dispositif). Une guirlande lumineuse est placée à l'intérieur de la boîte pour éclairer le dessous de la surface et assurer un éclairement continu et diffus : ainsi, la calibration de la caméra ne doit être faite qu'une seule fois. Par ailleurs, pour permettre à l'utilisateur d'interagir avec l'interface, un pavé numérique et un haut-parleur ont été intégrés au couvercle de la boîte. Il est aussi possible de brancher une souris, un clavier, un microphone ou un écran pour développer les applications ou diversifier les usages de la Tangible Box.

Conception d'applications pédagogiques pour la Tangible Box (Chapter 4, 4)

Séances de conception (Chapter 4, 4.1)
Afin de mieux cerner les usages potentiels de la Tangible Box, nous avons tout d'abord rencontré un professeur de mathématique, puis organisé une séance de brainstorming avec quatre professeurs spécialisés. Au cours de ces deux séances, de nombreuses activités ont été proposées, liées à différentes disciplines (mathématiques, anglais, histoire, géographie, Orientation & Mobilité, biologie, etc.). Nous avons identifié deux principaux types d'activités. Dans le premier cas, un seul objet tangible est utilisé et sert de curseur que l'élève peut déplacer sur la graphique pour obtenir des informations sur l'élément placé sous le curseur (par exemple, le nom des quartiers de New-York est donné quand un objet représentant un taxi est déplacé sur la carte). Dans ce cas, il peut être demandé à l'élève de suivre un chemin en particulier (par exemple, une courbe sur un graphe mathématique), et des instructions sont données pour guider l'élève ou lui indiquer qu'il n'est pas en train d'explorer la bonne partie du graphique. Dans le second cas, plusieurs objets sont utilisés, chacun représentant une information particulière (par exemple une ville, un évènement historique, un partie du corps humain, un point dans un repère cartésien), et les élèves doivent replacer les objets au bon endroit (en suivant ou non des instructions de guidage). De manière générale, ces deux sessions ont montré que les professeurs avaient parfois des difficultés à imaginer des activités pédagogiques qui s'appuieraient sur la possibilité de reconfigurer le graphe tactile grâce aux objets tangibles.

Proposition d'un cadre de conception (Chapter 4, 4.2)
Afin de pallier cette difficulté, nous avons proposé un cadre de conception pour la Tangible Box, composé de quatre thèmes : caractéristiques générales, matériel, activités et interactivité. Chaque thème présente un ensemble de leviers permettant de diversifier les applications pour la Tangible Box. Le premier thème concerne principalement les représentations graphiques utilisées : leur contenu peut être augmenté grâce à différents modes, et chaque graphique peut être utilisé pour des activités de complexité croissante, ou de nature différentes (e.g. découverte vs consolidation d'acquis). Le deuxième thème rappelle que différents supports peuvent être utilisés, et que les objets tangibles peuvent jouer différents rôles (ils peuvent par exemple servir de curseur, représenter une information, ou être utilisés pour sélectionner un item dans un menu). Le troisième thème décrit les grands types d'activités qui peuvent être envisagées : activité exploratoire (l'élève est libre d'interagir avec le système comme il le souhaite) ; activité expressive (l'élève construit lui-même une représentation) ; activité de type « essais et erreurs » ; évaluations. Ces activités requièrent une succession de tâches : exploration/manipulation ; édition/annotation ; construction ; reconstruction. Finalement, le dernier thème rappelle que plusieurs techniques d'interaction peuvent être envisagées, qu'elles soient basées sur l'utilisation de commandes vocales, du pavé numérique ou des objets tangibles.

Perspectives et discussion (Chapter 4, 6)
D'un point de vue matériel et logiciel, plusieurs aspects de la Tangible Box peuvent être améliorés : le système de fixation, la hauteur de la boîte, la puissance des aimants qui peuvent rapidement altérer le support utilisé et l'algorithme de détection des objets (robustesse, performance et précision des coordonnées calculées).

Le cadre de conception que nous avons proposé pourrait d'une part être complété et détaillé, et d'autre part servir à la conception d'autres interfaces tangibles pour l'apprentissage. En effet, les tâches que nous avons identifiées sont communes à plusieurs interfaces tangibles développées pour des personnes déficientes visuelles. Il serait aussi intéressant de réaliser des évaluations dans le but de mieux comprendre les bénéfices d'un type d'activité (e.g. « essais et erreurs ») en termes d'apprentissage. Par ailleurs, le cadre de conception pourrait être utilisé pour faciliter le développement d'applications par des développeurs, mais éventuellement par les professeurs eux-mêmes. Il serait par exemple envisageable de créer un ensemble de modules (e.g. un module TTS qui permettrait de paramétrer le volume, la langue, la vitesse, etc. ; un module « guidage » qui permettrait de choisir quel type d'instructions donner, à quelle fréquence, etc.).

Finalement, l'utilisation d'un smartphone permettrait de diversifier les usages de la Tangible Box, selon les principes de l'approche BYOD (*Bring Your Own Device*). Nous avons notamment identifié trois perspectives d'améliorations basées sur l'utilisation d'un smartphone : 1) détection des doigts de l'utilisateur et des objets grâce à un téléphone placé au-dessus de la Tangible Box, afin de permettre des interactions gestuelles et de simplifier la mise en place des activités (quand chaque objet doit être associé à une information particulière) ; 2) conception de menus à afficher sur le smartphone, pour faciliter la sélection d'activités ou l'activation de certaines fonctionnalités; 3) identification des élèves grâce à leur smartphone pour proposer des contenus personnalisés ou enregistrer des informations d'une session à l'autre (e.g. score, annotations).

CHAPITRE 5 – BOTMAP : *PAN* ET *ZOOM* AVEC UNE INTERFACE TANGIBLE ANIMEE

Les travaux présentés dans ce chapitre ont fait l'objet d'un article, en cours de soumission (ACM Transactions on Computer-Human Interaction) :

- J. Ducasse, M. Macé, B. Oriola, C. Jouffrais. *BotMap: non-visual panning and zooming for visually impaired users*. Article de journal.

Motivations (Chapter 5, 1)
Les deux projets présentés précédemment tirent profit de la possibilité de reconfigurer les interfaces en permettant aux utilisateurs de déplacer les objets pour (re)construire une carte, manipuler un diagramme, etc. Dans ce projet, nous avons voulu exploiter la possibilité d'utiliser des objets animés pour permettre à un utilisateur déficient visuel d'accéder à une carte dynamique. Dans cette étude, nous avons considéré deux actions essentielles lors de l'exploration d'une carte numérique : *zoomer* (pour changer d'échelle), et *panner* (pour déplacer une fenêtre de visualisation sur la carte – seule la partie de la carte contenue à l'intérieur de la fenêtre de visualisation est affichée à l'écran). Bien que ces deux fonctionnalités aient parfois été développées pour des personnes déficientes visuelles (notamment avec des tablettes braille), ni les techniques d'interaction utilisées ni leur impact sur la compréhension n'ont été formellement évalués.

Description du système et des deux interfaces (Chapter 5, 2)
Le système, nommé BotMap, se compose d'une table interactive sur laquelle sont disposés des robots, représentant les points d'intérêt, et sur laquelle une carte est affichée. Trois niveaux de zoom ont été définis : au niveau Métropole, seules les métropoles sont affichées (toute la carte est affichée à l'écran) ; au niveau Ville, les métropoles et les villes sont affichées ; au niveau Village, les métropoles, les villes et les villages sont affichés.

Pour obtenir le nom d'un point d'intérêt représenté par un robot, l'utilisateur doit sélectionner ledit robot en le pointant avec son index, sur lequel est fixé un marqueur. Le nom du robot est donné, suivi de son type (e.g. « Paris, métropole »). Des commandes vocales permettent à l'utilisateur d'écouter la *liste* des lieux affichés, d'obtenir l'*échelle* actuelle (e.g. « la fenêtre représente 200 km »), de *répéter* la dernière instruction, ou de placer le dernier lieu sélectionné au *centre* de l'écran.

Pour changer la position de la fenêtre ou l'échelle de la carte, l'utilisateur doit activer les modes Pan et Zoom grâce à des commandes vocales, puis interagir avec le clavier (interface Clavier, ou *Keyboard*) ou les curseurs (interface Curseur, ou *Sliders*). Pendant ces actions, le système donne des informations vocales : pour le mode Pan, il indique la position de la fenêtre par rapport à sa position initiale, i.e. au moment de l'activation du mode (e.g. « 3 heures, 200 km ») ; pour le mode Zoom, il indique le niveau de zoom sélectionné ainsi que l'échelle (e.g. « niveau Ville, la fenêtre représente 130 km ») ;

Interface Clavier (contrôle discret et positionnement relatif) (Chapter 5, 2.3.2)
Un pavé numérique est placé sur la droite de la table. Le cadre est virtuellement découpé en une grille de 3 x 3. Les touches + et - permettent à l'utilisateur de changer de niveau de zoom : lorsque l'utilisateur zoome, la partie de la carte affichée dans la case centrale de la fenêtre est agrandie de manière à occuper toute la fenêtre; lorsque l'utilisateur dézoome, la partie affichée est réduite de manière à occuper la case centrale de la fenêtre uniquement. L'utilisateur peut donc sélectionner une échelle par niveau de zoom uniquement. Les flèches directionnelles permettent à l'utilisateur de déplacer la fenêtre d'une ligne et/ou d'une colonne à la fois.

Interface Curseurs (contrôle continu et positionnement absolu) (Chapter 5, 2.3.3)
Trois robots (les curseurs) peuvent être déplacés à l'intérieur de rails situés de part et d'autre de la zone d'affichage. Un robot (à droite) permet à l'utilisateur de sélectionner une échelle (e.g. pour passer de 280 km à 60 km), et ainsi de changer de niveau de zoom. Deux robots (à gauche et en bas) permettent à l'utilisateur de contrôler la position verticale et horizontale de la fenêtre de visualisation : en les déplaçant à l'intérieur des rails qui représentent respectivement la hauteur et la largeur de la carte, l'utilisateur peut déplacer la fenêtre et ainsi choisir quelle partie de la carte il souhaite afficher.

Implémentation (Chapter 5, 3)
Un marqueur est fixé sur le haut des robots et sur un doigt de l'utilisateur pour obtenir leur position (les marqueurs sont repérés par une caméra suspendue au-dessus de la table). Les robots sont des Ozobots, de petits robots commercialisés et initialement destinés à l'apprentissage de la programmation par de jeunes enfants. L'application a été développée en Java, avec la bibliothèque MT4J. Un algorithme a été développé pour gérer le déplacement des robots (attribution des lieux et gestion des collisions).

Etude 1 : utilisabilité des interfaces (Chapter 5, 4)
L'objectif de cette étude était de s'assurer que les deux interfaces développées permettent de réaliser des actions de *pan* et *zoom*, sans vision. Nous souhaitions aussi étudier si une interface était plus utilisable qu'une autre. Pour cette étude ainsi que pour l'étude 2, les robots étaient replacés manuellement, par l'expérimentateur, afin de limiter le temps de l'évaluation.

Matériel et méthodes (Chapter 5, 4.1 et Chapter 5, 4.2)
10 personnes voyantes sous bandeau ont pris part à cette étude. La tâche était de trouver un village (nommé « Cible »), le plus rapidement possible. Une commande vocale (*Info*) permettait aux participants d'obtenir à tout moment la distance et la direction de la cible par rapport au centre de la fenêtre. Nous avons varié trois paramètres : la distance à la cible (petite *vs* grande), la direction de la cible (sur l'axe vertical ou horizontal *vs* en diagonale), et le niveau de zoom initial (niveau village, identique à la cible *vs* niveau métropole, différent de celui de la cible). Pour chaque condition, les sujets devaient trouver trois cibles, soit 24 essais par interface. Nous avons principalement mesuré le temps nécessaire pour trouver la cible et la distance parcourue.

Résultats et discussion (Chapter 5, 4.3 et Chapter 5, 4.4)
Tous les sujets ont réussi à trouver toutes les cibles, en 25 secondes environ. Deux tendances ont pu être observées : 1) avec les Curseurs, les sujets étaient considérablement plus longs lorsque la direction était Diagonale que lorsqu'elle était Verticale/Horizontale ; 2) les sujets avaient tendance à être plus longs avec les Curseurs qu'avec le Clavier lorsque la distance était petite et la direction diagonale. Des tendances similaires ont été observées en mesurant la distance parcourue : les sujets ont davantage déplacé la fenêtre avec les Curseurs qu'avec le Clavier lorsque la distance était petite, la direction diagonale et le niveau de zoom identique. En termes de satisfaction, le score SUS était proche de 86 pour les deux interfaces. En conclusion, les deux interfaces permettent à des personnes d'effectuer des opérations de *pan* et de *zoom* sans vision, et dans un temps relativement court. Les mesures observées tendent à montrer que l'interface Clavier est plus utilisable (temps de complétion plus courts et distances parcourues moins grandes).

Etude 2 : utilisabilité et représentations mentales (Chapter 5, 5)
Avec cette étude, nous souhaitions confirmer les tendances observées précédemment avec des utilisateurs déficients visuels, mais aussi étudier dans quelle mesure des personnes déficientes visuelles étaient capables de comprendre une carte nécessitant des opérations de type « *Pan* & *Zoom* ».

Matériel et méthodes (Chapter 5, 5.1 et Chapter 5, 5.2)
Nous avons recruté huit personnes déficientes visuelles (sans ou avec une très faible perception résiduelle). L'étude était composée de deux sessions de 2 h 30 environ, réalisées sur deux jours. La première session était une session d'entraînement (explication des concepts de *pan* et *zoom* et exercices avec les deux interfaces) ; la seconde session était une session d'évaluation, composée de deux blocs (un pour chaque interface). Les sujets devaient trouver des lieux dans une carte (fictive), et mémoriser la position de ces lieux afin de pouvoir répondre à des questions. Chaque bloc était composé de 8 essais : deux essais de type « Zoom » (pour trouver deux villes situées près d'une métropole) ; deux essais de type « Zoom & Pan » (pour trouver un village situé dans un rayon de 50 km autour d'une ville) ; deux essais de type « Pan » (pour trouver une ville située à plus de 150 km d'une autre ville) ; deux essais de type « Dézoom & Pan » (pour trouver deux villes situées près d'une métropole, elle-même située assez loin de la ville de départ). Pour chaque essai, la consigne était donnée (e.g. « trouver les villes A1 et A2 situées aux alentours de la métropole A »), puis les sujets devaient trouver les lieux cibles tout en mémorisant leur position. Une fois les lieux trouvés, ils avaient trente secondes pour explorer la partie de la carte affichée.

A la fin de chaque essai, les participants devaient répondre à quatre questions à choix multiples (une seule bonne réponse sur quatre possibles). Ces questions étaient simples (concernant un lieu par rapport à un autre) ou complexes (concernant un lieu par rapport à plusieurs lieux) ; portaient sur des distances ou des directions ; portaient sur un groupe de lieux (une métropole et ses villes et villages satellites) ou plusieurs groupes de lieux (plusieurs métropoles et leurs villes et villages satellites). A la fin des huit essais, les participants devaient reconstruire la carte grâce à des aimants sur lesquels l'initiale de chaque lieu était inscrite en Braille.

Résultats (Chapter 5, 5.3)
Navigation (Chapter 5, 5.3.1)
115 essais sur 128 ont été correctement réalisés par les participants, sans l'aide de l'expérimentateur. La plupart des essais incorrects étaient des essais de type « Zoom & Pan », lors desquels les sujets se sont sentis désorientés (i.e. ils n'arrivaient pas à savoir où se situait la fenêtre et/ou comment déplacer la fenêtre pour trouver la cible). De même que pour l'étude 2, les temps de complétion et les distances parcourues étaient considérablement plus longs avec les Curseurs qu'avec le Clavier.

Représentations mentales (Chapter 5, 5.3.2)
Les cartes reconstruites ont été analysées grâce à une méthode de régression bidimensionnelle : le coefficient de régression indique dans quelle mesure les cartes reconstruites sont similaires à la carte modèle. De manière générale, la plupart des cartes reconstruites étaient (très) similaires au modèle (le coefficient de huit cartes était supérieur à 0,8 et le coefficient de six cartes était compris entre 0,6 et 0,8). Il est possible de distinguer trois groupes de participants : deux ont obtenus de faibles coefficients (< 0,5), six ont obtenus de bons coefficients (entre 0,7 et 0,8) et un participant a obtenu d'excellents résultats (> 0,95). Il n'y avait pas de différences entre les interfaces Clavier et Curseurs.

Quant aux questions, le taux moyen de bonnes réponses était considérablement supérieur au niveau de chance, qui était de 25% (environ 56% pour les Curseurs et 63% pour le Clavier). Le pourcentage de bonnes réponses était cependant plus faible pour les questions de type Distance, notamment pour l'interface Curseurs. De manière générale, le taux de bonnes réponses étaient plus élevé pour l'interface Clavier que pour l'interface Curseur, quel que soit le type de questions.

Questionnaires (Chapter 5, 5.3.3)
Le score SUS était d'environ 77 pour le Clavier (IC95% [68, 84]) et de 73 pour les Curseurs (IC95% [61, 82]). L'interface Clavier a été préférée par la plupart des participants (6 l'ont trouvée plus efficace, 5 l'ont trouvée plus agréable à utiliser et 5 l'ont classée première). Les résultats du NASA-TLX ont révélé que la tâche était mentalement exigeante, et nécessitait des efforts assez élevés.

Discussion (Chapter 5, 5.4)
Cinq principales remarques peuvent être faites suite à cette étude. Premièrement, les mesures de compréhension ont montré que des personnes déficientes visuelles sont capables de comprendre des cartes nécessitant l'utilisation de « *Pan* & *Zoom* », et que, par conséquent, l'expérience visuelle n'est pas nécessaire pour comprendre et manipuler les concepts de *pan* et de *zoom*.

Deuxièmement, les résultats de ces deux premières études semblent indiquer que le Clavier est plus utilisable que les Curseurs. Ceci pourrait s'expliquer par le fait qu'il pouvait y avoir un décalage entre les informations données par le système et la position des curseurs (à cause de la nature séquentielle des retours sonores). Par ailleurs, les personnes déficientes visuelles ne sont pas habituées à manipuler des dispositifs de contrôle continu, ce qui pourrait expliquer les préférences rapportées.

Troisièmement, bien que les participants aient réussi à réaliser les actions de *pan* et *zoom* nécessaires à la réalisation de la tâche, certains ont rencontré des difficultés et se sont sentis désorientés, notamment pour les essais de type « Zoom & Pan ». Plus précisément, il semblerait que les participants n'aient pas toujours réussi à mettre en œuvre les stratégies de navigation qu'ils avaient planifiées (e.g. certains participants souhaitaient tourner autour d'un point de référence mais n'arrivaient pas à déplacer la fenêtre tout en restant dans un certain rayon). Ces difficultés pourraient s'expliquer par un manque d'entraînement ou par la nature des informations fournies par le système (coordonnées polaires et informations relatives à la position initiale de la fenêtre).

Quatrièmement, nous avons observé des relations entre les performances en termes de navigation et les performances en termes de compréhension : les sujets qui ont obtenu de bons scores de compréhension étaient enclins à naviguer correctement avec les deux interfaces, et ceux qui ont eu des difficultés à manipuler une interface étaient enclins à obtenir de moins bons résultats en termes de compréhension. Ces différences inter-individuelles ne peuvent être expliquées par l'âge ou l'expérience visuelle des sujets (des sujets aveugles tardifs ont obtenu de moins bonnes performances que des aveugles de naissance). En revanche, ces différences pourraient s'expliquer par des stratégies de mémorisation différentes (les deux sujets ayant obtenu les moins bonnes performances étant aussi ceux qui ont adopté des stratégies de mémorisation différentes des autres).

Cinquièmement, il apparait que l'exploration non-visuelle de cartes de type « *Pan* & *Zoom* » est mentalement exigeante. Cette observation pourrait être liée aux conditions de l'évaluation (nouveaux concepts de *pan* et *zoom*, nouveau système avec plusieurs commandes vocales à retenir, tâche nécessitant de mémoriser des noms de lieux et des positions géographiques, etc.). Cependant, il est aussi possible de concevoir des aides à la navigation afin de libérer des ressources cognitives pour l'utilisateur.

Etude 3 : scénario réaliste et aides à la navigation (Chapter 5, 6)

Dans cette étude, nous avons souhaité tester le système dans un cadre plus réaliste, i.e. avec des données géographiques réelles et les robots en fonctionnement. La carte utilisée était la carte d'Afrique, avec 6 mégalopoles, 27 métropoles et 127 villes. Afin de faciliter la navigation (et éventuellement réduire la charge cognitive induite par la tâche), nous avons aussi développé quatre aides à la navigation.

Aides à la navigation (Chapter 5, 6.2.3)

Toutes les aides à la navigation peuvent être activées par commande vocale. La commande « Départ » réinitialise le niveau de zoom et la position de la fenêtre dans leur configuration initiale (i.e. toute la carte d'Afrique est affichée, au niveau mégalopole). La commande « Où suis-je … » permet à l'utilisateur de se repérer sur la carte. Dans un premier temps, le système indique la position du cadre (en haut à droite, en bas à gauche, etc.). Puis, selon le niveau de zoom actuel, différentes informations sont données (par exemple, au niveau Métropole : « la métropole la plus proche de A est B, située à 6 h et 900 km ; la mégalopole la plus proche de A est C, située à 9 h et 2000 km »). La commande « Où est … » indique à l'utilisateur où se trouve le lieu concerné (distance et direction) par rapport au dernier lieu sélectionné, ou, si le dernier lieu sélectionné n'est plus affiché à l'écran, par rapport au centre de la fenêtre. Enfin, la commande « Aller à … » permet à l'utilisateur d'afficher n'importe quel lieu au centre de la fenêtre ; le niveau de zoom est modifié en conséquence (niveau Ville si le lieu demandé est une ville).

Matériel et méthodes (Chapter 5, 6.1 et Chapter 5, 6.2)
Trois personnes déficientes visuelles ayant participé à l'étude 2 ou aux pré-tests ont été recrutées, ainsi que trois personnes voyantes (sous bandeau). Les sujets devaient trouver l'itinéraire le plus court reliant trois lieux ; entre deux lieux, ils devaient trouver une métropole et une ville touristique à visiter (le message « tourisme » était joué lors de la sélection du lieu, s'il était touristique). Il n'y avait aucune contrainte de temps : les sujets s'arrêtaient quand ils étaient satisfaits de leur itinéraire. Ils devaient ensuite répondre à trois questions pour chaque aide à la navigation (facilité d'utilisation, utilité, améliorations possibles) et commenter huit caractéristiques des robots (« discriminabilité », hauteur, interactivité, forme, vitesse, stabilité, bruit, nombre).

Résultats (Chapter 5, 6.3)
Aides à la navigation (Chapter 5, 6.3.1)
Toutes les aides ont été jugées très faciles à utiliser, et très utiles. La commande « Où est… » a été très fréquemment utilisée, ainsi que la commande « Aller à … ». En revanche, les deux autres commandes n'ont été que très rarement utilisées (les sujets ne se sont pas sentis désorientés). Plusieurs personnes ont mentionné le fait qu'elles aimeraient une commande permettant de filtrer les informations affichées.

Robots (Chapter 5, 6.3.2)
Le temps moyen de replacement des robots était de 9 secondes. Les sujets étaient particulièrement satisfaits de la hauteur et de la forme des robots, ainsi que du bruit émis lorsqu'ils se déplacent (qui permet de savoir que le système fonctionne). En revanche, les commentaires concernant les autres caractéristiques étaient plus mitigés : la vitesse a dans l'ensemble été jugée convenable, mais des sujets auraient aimé que les robots soient un peu plus rapides ; la stabilité des robots est convenable, mais le système serait plus utilisable si les robots étaient plus stables. Quant au nombre de robots utilisé, certains sujets l'ont jugé satisfaisant (voire idéal), alors que d'autres auraient souhaité pouvoir interagir avec davantage de robots.

Discussion et perspectives (Chapter 5, 7)
Le développement de BotMap nous a permis de mettre en évidence le potentiel des interfaces tangibles animées pour rendre accessibles des cartes géographies dynamiques. Les trois études réalisées nous ont permis d'évaluer l'utilisabilité du système, et plus particulièrement des deux interfaces que nous avons développées, ainsi que leur impact sur les représentations mentales des participants.

Cette étude a ouvert de nombreuses perspectives. En termes d'implémentation, il serait intéressant d'utiliser des robots plus stables et plus rapides, voire fournissant des retours haptiques. Le contenu pourrait aussi être enrichi en permettant à l'utilisateur d'utiliser les robots comme dispositif d'entrée ou en concevant un système combinant BotMap avec les Tangible Reels. Concernant l'utilisabilité des techniques, il serait intéressant d'étudier si avec davantage d'entraînement, les participants arriveraient à tirer profit de l'interface Curseurs (contrôle continu), et si cela impacterait leur compréhension de la carte. De manière générale, l'exploration d'une carte de type « *Pan* & *Zoom* » semble demander beaucoup d'efforts d'un point de vue cognitif ; il serait ainsi souhaitable d'étudier si d'autres retours (e.g. sonores au lieu de vocaux) ou d'autres techniques d'interaction (e.g. une fenêtre tangible à déplacer sur une carte) pourraient réduire la charge cognitive. Finalement, si de tels systèmes venaient à être plus largement utilisés, il serait nécessaire de réfléchir à l'adaptation automatique de contenu pour répartir les informations sur plusieurs niveaux de zoom et/ou à réfléchir à d'autres façons de représenter l'information grâce à des robots (par exemple, un robot pourrait représenter plusieurs villes).

CHAPITRES 6 ET 7 – DISCUSSION, PERSPECTIVES ET CONCLUSION

Contributions (Chapter 1, 5 et Chapter 6, 1)
D'un point de vue théorique, les principales contributions de cette thèse sont la proposition d'une nouvelle classification des cartes et diagrammes interactifs pour les personnes déficients visuelles, la mise en évidence du potentiel des interfaces tangibles pour les personnes déficientes visuelles, et l'analyse détaillée de plusieurs prototypes de cartes et diagrammes tangibles. Etant donné le faible nombre de travaux de recherches portant sur les interfaces tangibles pour les personnes déficientes visuelles, nous avons cherché à apporter des solutions à plusieurs verrous techniques, notamment concernant la conception d'objets tangibles stables, la conception de techniques d'interaction adaptées et le développement de nouvelles interfaces. Nous avons notamment proposé trois nouvelles approches pour rendre les représentations graphiques tangibles plus expressives et/ou complexes : la matérialisation de symboles linéaires (Tangible Reels), l'utilisation d'objets tangibles au-dessus de supports tactiles traditionnels (Tangible Box), et l'utilisation d'objets tangibles animés (BotMap). Nous avons conçu plusieurs techniques d'interaction pour la reconstruction de représentation graphiques (avec notamment une technique de guidage en deux temps), l'exploration et l'annotation de graphes tangibles, et l'exploration de cartes de type « *Pan* & *Zoom* ».

Le développement et l'évaluation de ces trois interfaces nous a aussi permis de démontrer qu'il est possible de rendre des représentations graphiques relativement complexes et expressives grâce à l'interaction tangible. Contrairement aux prototypes existants, les trois interfaces que nous avons développées permettent en effet à des utilisateurs déficients visuels d'accéder à des représentations graphiques variées (cartes dynamiques, histogrammes, organigrammes, horloge, etc.) et reconfigurables. A travers cette thèse, nous avons aussi identifié un certain nombre de tâches pouvant être réalisées avec des cartes et des diagrammes tangibles, et mis en évidence leur potentiel pour des activités pédagogiques, notamment grâce au cadre de conception que nous avons proposé pour la Tangible Box.

Portée de la thèse (Chapter 6, 2)
Les interfaces que nous avons conçues l'ont été de manière à ce qu'elles puissent être utilisées par des personnes aveugles. Cependant, il serait intéressant de voir comment les solutions que nous

avons proposées en termes de conception pourraient être adaptées à des personnes malvoyantes ou voyantes. Notre approche pourrait ainsi converger avec le concept de *Feelable User Interface*, un type d'interface tangible à destination de personnes voyantes qui ne s'appuie sur aucun retour visuel.

Comme nous l'avons déjà souligné, la plupart des projets de recherche portant sur l'accessibilité des représentations graphiques tendent à porter sur un type de graphe précis (e.g. un histogramme) ou un type de carte précis. Nous avons volontairement choisi de considérer à la fois les cartes et les diagrammes, car ces deux types de représentations graphiques s'appuient sur les mêmes primitives graphiques (points, lignes, aires), et, par conséquent, soulève les mêmes problèmes de conception. Cependant, il serait intéressant d'étudier comment rendre plus utilisable un type de carte ou de diagramme en particulier en proposant des fonctionnalités adaptées. De manière générale, les contributions de cette thèse pourraient servir de base à la conception d'interfaces tangibles destinées à rendre accessibles des tableaux de données (les objets pourraient servir à annoter une cellule par exemple), ou des données qui ne sont pas intrinsèquement spatiales (éléments d'un langage de programmation, d'un jeu, d'un récit, etc.).

Relation avec d'autres domaines de recherche (Chapter 6, 3)
Les travaux que nous avons réalisés sont en lien avec cinq domaines de recherche. Premièrement, les théories d'*embodiment* fournissent un cadre d'étude intéressant pour analyser le potentiel des interfaces tangibles pour l'apprentissage (Chapter 6, 3.1). Il serait par exemple intéressant de s'appuyer sur ces théories pour étudier si le fait de reconstruire une carte facilite la mémorisation de ladite carte (e.g. dans le cadre des Tangible Reels).

Deuxièmement, de nombreux travaux ont été conduits sur les *constructive assemblies* – des interfaces tangibles qui s'appuient sur la construction libre de représentations ou de modèles à partir de briques tangibles qui peuvent être connectées l'une à l'autre (Chapter 6, 3.2). Ces travaux, qu'il s'agisse de cadres de conception, de modèles théoriques ou de prototypes, pourraient non seulement servir de base à l'amélioration des Tangible Reels, mais aussi servir au développement de *constructive assemblies* pour des personnes déficientes visuelles.

Les interfaces de type *token+constraint* constituent le troisième domaine de recherche auquel cette thèse est liée (Chapter 6, 3.3). Avec ces interfaces, la fonction ou la signification des objets tangibles est déterminée par des contraintes physiques qui restreignent la façon dont ils peuvent être manipulés (e.g. un curseur dans un rail). Dans le cadre de la Tangible Box, l'utilisation d'objets tangibles en sus de supports tactiles ouvre de nombreuses perspectives pour le développement d'applications pédagogiques basées sur des relations *token+constraint* ; en effet, les éléments tactiles peuvent plus ou moins contraindre la manipulation des éléments tangibles.

Le quatrième domaine de recherche concerne les *Swarm User Interfaces,* des interfaces tangibles sur table composées d'un ensemble de petits objets animés (Chapter 6, 3.4). Bien que BotMap ne réponde pas à tous les critères d'une SUI, le système pourrait être amélioré et/ou complété en s'appuyant sur un cadre de conception récemment proposé. Il serait ainsi envisageable d'utiliser des robots de différentes formes, de proposer des animations tangibles pour faciliter la compréhension de la carte, de permettre à l'utilisateur d'interagir avec un seul robot (par exemple pour sélectionner les informations lues par la voix de synthèse), ou d'utiliser les robots au-dessus d'un support tactile.

Enfin, nos travaux sont très liés à un domaine de recherche émergent, appelé *data physicalization*, et qui a pour objet d'étude les représentations physiques de données, qui peuvent faciliter la communication, l'apprentissage ou encore la prise de décision (Chapter 6, 3.5). Bien que les études sur ce sujet soient limitées, le développement de *data physicalizations* pour des personnes déficientes visuelles pourrait d'une part s'inspirer des prototypes et études existants, mais aussi inspirer le développement de *data physicalizations* pour les personnes voyantes.

Perspectives générales (Chapter 6, 4)
La dernière partie du chapitre 6 de la thèse est consacrée à trois grandes perspectives. Dans un premier temps, il serait souhaitable d'améliorer les interfaces proposées (voire de les combiner), en s'appuyant notamment sur la conception de retours sonores courts (afin d'éviter des décalages entre la représentation physique et les messages lus par le système), et sur le développement de techniques d'interaction pour l'exploration de lignes et d'aires sonores et/ou haptiques (afin de rendre les représentations plus expressives). Deux champs d'applications pourraient aussi être considérés : d'une part, les situations collaboratives d'apprentissage (deux projets sont actuellement en cours sur ce sujet – l'un concerne le développement d'un jeu, l'autre le développement d'activités pédagogiques pour accompagner des enfants déficients visuels dans leur apprentissage des concepts spatiaux) ; d'autre part, l'accessibilité des données géo-statistiques grâce au développement d'une interface tangible et animée (*geophysicalization*) – à ce titre, un histogramme motorisé a été développé, qui pourrait être utilisé avec BotMap pour explorer, comprendre et analyser des données géostatistiques.

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