Tangible Reels: Construction and Exploration of Tangible Maps by Visually Impaired Users

Julie Ducasse[1], Marc Macé[2], Marcos Serrano[1], Christophe Jouffrais[2]

[1] University of Toulouse – IRIT
Toulouse, France
{first_name.last_name}@irit.fr

[2] CNRS - IRIT
Toulouse, France
{first_name.last_name}@irit.fr

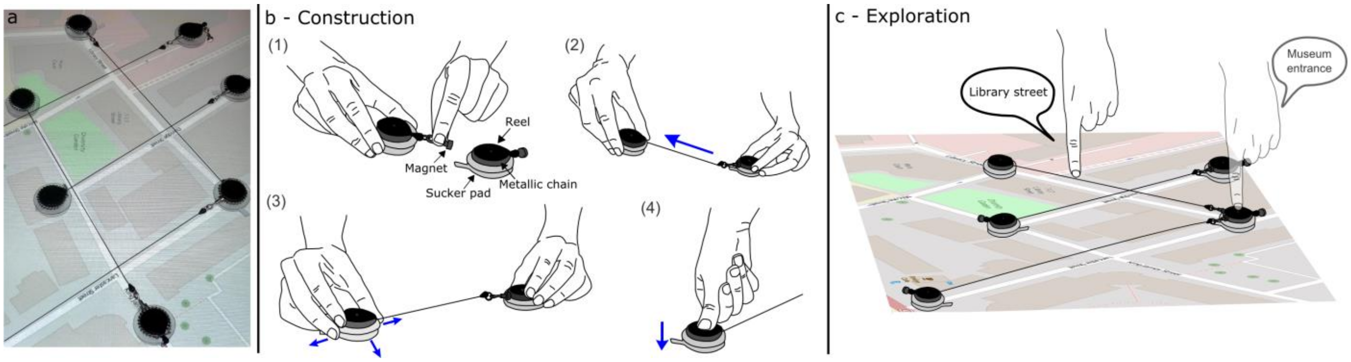

Figure 1. a) The interface enables a visually impaired user to render digital maps tangible by using Tangible Reels. b) The user is guided step by step to correctly place each Tangible Reel. To construct a line, the user attaches two Tangible Reels (b1), follows rough (b2) and fine (b3) audio guidance instructions, and presses the sucker pad (b4). c) The user can explore the tangible map, receiving auditory feedback when pointing at lines and pads.

ABSTRACT
Maps are essential in everyday life, but inherently inaccessible to visually impaired users. They must be transcribed to non-editable tactile graphics, or rendered on very expensive shape changing displays. To tackle these issues, we developed a tangible tabletop interface that enables visually impaired users to build tangible maps on their own, using a new type of physical icon 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.

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INTRODUCTION
In educational centers for blind and visually impaired people, graphical representations such as charts, schemas and maps are widely used in STEM fields (Science, Technology, Engineering and Mathematics), but also during orientation and mobility lessons [16]. As visual graphics are inherently inaccessible to visually impaired users, they must be transcribed into tactile graphics. In this study we observed usages in a specialized Institute: visual graphics are transcribed into raised-line, hand-crafted or magnetic graphics. The production of the first two types relies on a time-consuming process that needs to be done by a tactile graphics specialist [30], and results in non-editable maps [10]. Magnetic maps are easier to produce and more adjustable, but they cannot be constructed or accessed by visually impaired users without assistance.

These issues can be alleviated by automating the production of graphics or maps (see [30]) and/or making them interactive. However interactive graphics are also limited: audio-tactile graphics cannot be edited [2], and acoustic and/or haptic graphics (see [31]) usually enable exploration based on a single point of contact only. Shape-changing displays are very promising but are still extremely expensive [29].

We aimed to overcome these limitations by providing visually impaired users with a way to construct physical representations of visual graphics on their own. Tangible tabletop interfaces are, in this sense, particularly relevant, as they provide a way to interact with digital information via the manipulation of phicons (i.e. physical icons, as defined in [9]), and therefore also provide a way to translate digital information into a physical form. A tangible interface for the exploration of graphs by visually impaired people has previously been implemented [18]. Although it provided a limited accessibility to mathematical plots with a limited number of points, it was a rousing first step towards non-visual tangible interfaces. We intended to design a low cost device that is accessible to visually impaired users without any assistance, and that allows them to render tangible any digital graphical content that is composed of points and lines. It should complement existing tools (e.g. raised-line maps) because it allows dynamic construction and exploration of graphics (with the benefit of "learning-by-doing"), without the restriction of a single point of contact exploration. In this study, we designed and constructed a novel type of physical icon called Tangible Reels. A Tangible Reel is composed of a sucker pad that ensures stability, and of a retractable reel that is used to create physical links between phicons. We also developed a non-visual tabletop interface that enables a visually impaired user to build a tangible map using Tangible Reels and to interact with it (see Figure 1). During the construction, audio guidance is provided so that the user can place the phicons correctly. As each phicon can be linked to another with the string of a retractable reel, lines can be constructed between two Tangible Reels. During tactile exploration, the user can listen to the name of the digital points and lines by performing a tap and hold gesture on their physical representations.

This paper describes three main contributions: 1) we report on observations of the use and production of tactile maps in a specialized educational Institute; 2) we describe the design process of Tangible Reels, and report on the evaluation conducted to check that Tangible Reels are stable, easy to manipulate, and that the physical representations built with them can be understood by a visually impaired user; 3) we introduce a novel interface that enables a visually impaired user to independently make digital maps tangible. We report on its evaluation, consisting in constructing and exploring four maps of increasing complexity.

OBSERVATION: USAGE OF TACTILE MAPS

The term "graphics" brings together a variety of materials whose spatial layout is used to provide content or data to the reader: diagram, figure, drawing, map, etc. [27] Maps are particularly interesting as they are essential in our day-to-day life, but also because they require the reader to understand and mentally integrate the spatial layout of the elements. The various types of maps (metro map, overview map, itineraries, etc.) clearly illustrate how diverse the complexity of tactile graphics can be. In this study, we chose to focus on the construction and exploration of maps.

To better understand how and why tactile maps are used in specialized educational centers, we observed two geography lessons with four students, one orientation and mobility (O&M) lesson with one student, and interviewed a geography teacher and two O&M instructors in the CESDV-IJA Institute in Toulouse, France. This Institute provides education and training for around 120 visually impaired people, from early childhood to later adulthood. We identified three types of maps: raised-line, magnetic and hand-crafted.

Figure 2. a) A raised-line map. b) A wooden model used for orientation and mobility lessons. c) Magnets are used to represent itineraries.

Raised-line maps are mainly used by geography teachers. In this Institute, they are made with thermoforming or swell-paper techniques but other techniques exist [4]. Thermoforming consists in placing a sheet of plastic upon a hand-crafted mold made of different textured papers. When heated in a vacuum, the plastic sheet is shaped by the mold and permanently deformed. Swell-paper maps are printed on a special heat-sensitive paper that swells when heated and creates relief.

Each teacher owns different maps whose content may differ depending on the age, ability and visual impairment of the students. During a lesson, teachers often need to use different maps as the amount of information that can be displayed on a tactile map is limited, but also because they usually do not include more than five different textures on a given map. This number can be increased when the students are progressively introduced to new textures. However, since a tactile map cannot be readily edited, several versions of the same map are used to introduce a limited set of textures (1-3) each time. In the Institute, four transcribers produce around 1200 tactile documents each year.

Magnets are more often used by O&M teachers to help a student learn an itinerary (see Figure 2c). 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 complex spatial configurations (road crossing or configuration of a building for example).

We also observed a number of hand-crafted graphics made out of rope, wood, felt or cardboard. They represent geometrical concepts (shapes, open/close features, parallel/perpendicular) and O&M elements (different types of crossings and a map of the school neighborhood for example).

These observations highlight one major issue: when a map is required, it has to be "materialized" with the assistance of a sighted person, which is a time consuming process. The students cannot access digital maps immediately and independently. Furthermore, the maps that are produced this way are not interactive and not editable, which limits the way users can interact with them and hence their autonomy.

To be fully accessible for visually impaired users, maps should be available without assistance and instantly. In addition, they should be interactive and editable, so that they could support dynamic operations such as zooming, panning, annotations, as well as other advanced functions (e.g. computing distances).

RELATED WORK ON INTERACTIVE MAPS

To alleviate the aforementioned issues, different approaches relying on new technologies have been used. Zeng and Weber [31] classified the different types of interactive maps in four categories, depending on the device and interaction used. Virtual acoustic maps use verbal and non-verbal audio output to render geographical data. For example, Zhao et al. [33] presented thematic maps explored with a keyboard or a tablet and producing string pitch and spatial sound. Virtual tactile (or haptic) maps most often rely on a force-feedback device. For instance, SeaTouch [26] enables visually impaired users to explore a maritime environment relying on haptic feedback, sonification and speech synthesis. The BATS [20] or HapticRiaMaps [11] are other examples of virtual tactile map using force-feedback devices. TouchOver map [22] provides visually impaired users with a basic overview of a map layout displayed on a mobile device through vibrational and vocal feedbacks. Kane et al. [13] described complementary non-visual interaction techniques that allow finding a target on large touch screens. Audio-tactile maps consist in a raised-line paper map placed over a touch-sensitive screen that provides audio descriptions of tactile elements when touched (see [19] and [30]). In contrast to virtual acoustic and tactile maps, these maps provide multiple points of contact (potentially all the fingers), and proved to be usable for learning spatial configurations [2]. Finally, Braille maps displayed on refreshable displays are a promising approach to create interactive maps. Zeng et al. [32] used a BrailleDis 9000 tablet device consisting in a matrix of 120x60 pins that can be moved up or down. Their prototype allowed visually impaired users to explore, annotate and zoom in or out. Similarly, Schmitz and Ertl [23] used a HyperBraille to present different types of maps representing buildings or large outdoor areas. The main drawback of the virtual maps is that they provide a single point of contact (e.g. a phantom device), which forces the user to explore the map sequentially, and mentally integrate a large amount of information through space and time. However, they do not require a raised-line map overlay and can theoretically allow panning, zooming, and dynamic updating. Refreshable displays can provide both multiple fingers exploration as well as dynamic update, but these devices are extremely expensive, and hence relatively unusual.

Tangible maps for the visually impaired may present a number of advantages: they could be built autonomously using appropriate feedback, which may support learning-by-doing activities, provide multiple fingers exploration and allow dynamic updating while being affordable.

Towards tangible maps

A number of tangible user interfaces have been developed to enable sighted users to interact with a map. GeoSpace [9] is an interactive map onto which objects are placed. Their location modifies the digital map position and extent. Urp [28] allows urban planners to simulate wind flow and sunlight, and to observe their consequences on physical building models placed onto the tabletop. With the MouseHouse Table [8], users can model several arrangements of urban elements such as streets and buildings by placing paper rectangles on the table and visualizing the behavior of pedestrians.

Two devices have been specifically designed for visually impaired users. The Tangible Pathfinder [25] allows them to construct a map using small objects that represent pavements, sidewalks, etc. Audio instructions and feedback assist the user in placing the objects and exploring the map. Schneider et al. [24] designed a prototype for route construction by telling the user the length of building blocks and where to place them on a magnetic board. These devices are devoted to route or neighborhood exploration, and can hardly be adapted to other types of graphical content. In addition, to our knowledge, they have not been formally evaluated, and the construction of a tangible map by a visually impaired user on its own has not yet been demonstrated. In this study, we designed and evaluated a tabletop tangible interface that enables a visually impaired user to construct and explore different types of maps, with different levels of complexity.

The current work is in line with two other research projects [17][18]. In [17] the device provides visually impaired users with multimodal feedback to accurately place objects (called TIMMs) in order to create and modify graphs and diagrams. The authors suggest that a tactile line could be added between two TIMMs with a piece of yarn for example, but did not indicate how the user would select the correct length and could interact with the line. In [18], the device allows the exploration of line graphs and bar charts. Phicons are placed in a restricted physical grid (9x7 cells) in order to represent the top of a bar or the turning point of a linear function. Relying on an evaluation with four users, the authors observed that the objects were regularly knocked over during the exploration. Hence they provide a few recommendations concerning the design of phicons for visually impaired users.

This review of the literature highlights three important points. First, although tangible user interfaces are promising to address some limitations of interactive tactile maps, research projects about autonomous construction of maps by visually impaired users are seldom. Second, the last two prototypes described above have only focused on rendering punctual symbols tangible (i.e. physical and associated to a digital content). Obviously, it is essential to make lines tangible as well because they are mandatory in maps and other graphical representations. Third, the question of how to design phicons that are stable and reliable has not been fully addressed yet. The magnetic board used in [24] is stable but may be unreliable. The objects are tracked by a camera placed above the tabletop, whose view may be occluded by users' hands. McGookin et al. [18] used a physical grid that holds the objects, which limits their potential location, but still observed unintentional knocks. In addition, such a solution is not relevant for the construction of most graphics that include lines and not only points.

MAKING DIGITAL MAPS TANGIBLE

In this section, we describe the characteristics of graphics that should be made with the system, the design of the Tangible Reels (they are tracked by the tabletop, and physically linked to each other to represent digital points and lines), and the interaction techniques designed to construct and explore maps.

Digital and physical maps

First of all, it is important to know that simplification of graphics is mandatory for tactile exploration [4]. Hence, fine details of an outline must be removed during this adaptation process and curves are most often straightened. In our system, maps are defined by a set of points and lines using a simple syntax: each point is associated with an ID, a name and two coordinates; each line is associated with an ID, a name and the IDs of starting and ending points. The system does not aim at the construction of detailed maps (such as mobility maps), but rather at the construction of sparse spatial configurations such as overview or metro maps.

Design of the Tangible Reels

To build the physical representation of a digital map, it was essential to provide the user with a way to draw lines of different lengths. Retractable reels appeared to be an appropriate tool as their strings can be pulled out to different lengths. This is more usable than using material of different lengths (e.g. pre-cut wool yarn such as in [17]) and limits the number of required steps and therefore the likelihood of errors. Retractable reels have already been used in the field of HCI research as input devices (see e.g. [14][1][21]).

According to [18], it was also essential to firmly set the objects to the table so that a visually impaired user could explore the map without moving them or knocking them over. This was even more important in our case as a tension was applied to the objects by the retractable reels. We identified three requirements for the design of the Tangible Reels. They had to be: easy to move during construction but stable during exploration; identifiable and trackable by the system; as small as possible to maximize the number of objects that can be placed onto the tabletop.

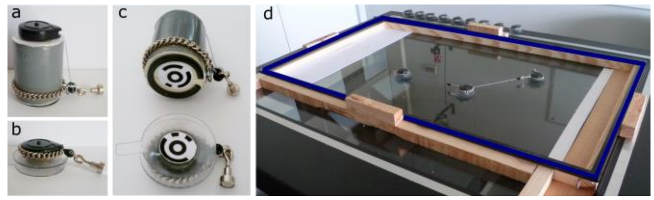

Figure 3: Weights (a) and Sucker pads (b) are two designs of Tangible Reels. c) A tag is positioned underneath so that they can be tracked by a camera placed under a plate glass (d). An infrared frame (highlighted in blue) detects the users' fingers during exploration.

We tried a number of adhesive materials such as Blu-Tack, glue dots, adhesive tape, Wikki Sticks, anti-slip gel pads or electrostatic screen protectors but none of them fulfilled the first two requirements. Finally we end up with two types of objects fulfilling the requirements: small plastic cylinders filled with lead called Weights, and flat Sucker pads (see Figure 3).

Weights

Weights were inspired by [18] who suggested "varying the weight" of the phicons 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 (Figure 3c). 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 (1cm. high) to keep it close to the tabletop.

Sucker pads

Sucker pads can easily slide along a smooth surface such as the tabletop screen, and strongly stick to the screen when pressed. We used 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 3c). The reel was glued onto the top. The sucker pads can easily be detached by pulling on a small strip that extends from its base.

Add-ons

Reels can be harmful when the string retracts. They can also apply a strong tension to the objects they are attached to and make them move. Therefore we used retractable reels with a lock/unlock button. Besides, to make it easier to link two objects, we fixed a strong neodymium magnet at the extremity of the reels' strings, and added a metallic bracelet to the objects. The bracelet was wrapped around the bottom part of the cylinder for the Weights and around the reels for the Sucker pads.

CONSTRUCTION AND EXPLORATION TECHNIQUES

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 (see Figure 3d). During exploration, the user can retrieve the name of the points and lines using finger interactions. All the values mentioned afterward (distances and timers) were based on observations made during preliminary tests.

Constructing the map

Construction instructions

Each line is constructed using two Tangible Reels attached to each other. Three instructions indicate to the user what is the next action to perform (see Figure 1):

- *"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. As soon as the Tangible Reel is detected, guidance instructions are provided.
- *"Attach an object to the right/to the left/below/above"*: 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 last one that was placed.
- *"Attach an object to <name of the object>, to the right/to the left/below/above"*: The start 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 to.

Feedback

- "*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.
- *"Object lost":* The user is informed when 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.

Guidance instructions

Depending on the distance between the Tangible Reel that the user is currently moving and the position of the target point, two types of guidance instructions are provided: rough guidance (every 3500 ms) and fine guidance instructions (every 1500 ms).

- *Rough guidance instructions* (Figure 1b, step 2). When distance is superior to 15 cm, the system indicates the direction of the target (up / down / left / right / up and right / down and right / up and left / down and left) 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 1b, step 3). 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.

Exploring the map

When exploring the map, the user can listen to the name of a point or a line by performing a tap and hold gesture above it. To avoid unintentional selections, the user must select one point or line at a time for at least 700 ms (see Figure 1).

IMPLEMENTATION

Hardware

Our tabletop was a 100 x 100 cm plate glass. The setup also included a projector to illuminate the surface and a webcam to detect tagged objects. Both were placed beneath the plate glass. A multitouch IR frame was placed two centimeters above the plate glass (Figure 3d) in order to detect the fingers. To achieve a high quality of tag detection, we restricted the area of work to 80 x 57 cm. The projector, webcam and IR frame were connected to a laptop.

Software

The Tangible Reels were tracked using the TopCodes library [7], which allowed using small circular tags that fit under the objects. The IR frame sent messages containing the finger input state (pressed, updated or ended) and position using the TUIO protocol [12]. We used the MultiTouch4Java library (MT4J, [15]) to receive TUIO messages, and to display the image of the map when needed (e.g. for debug) as well as the position of the physical objects and lines. Audio instructions were provided with a SAPI4 compliant Text-To-Speech engine distributed as part of the CloudGarden TalkingJava SDK 1.7.0.

PRE-STUDY: TANGIBLE REELS USABILITY

The aim of this pre-study was to investigate whether the two types of Tangible Reels were stable and easy to manipulate, but also to verify that built tangible maps were understandable by visually impaired users. It was done for testing the object design only and was performed without any interactive instruction or feedback. We used two types of maps that are frequently used by visually impaired users: metro maps and overview maps (Figure 2a). The Braille Authority of North Canada 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".

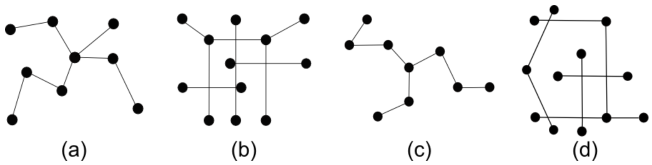

Figure 4: A set of adapted maps used for the exploration task (a, b) and for the construction task (c, d). (a) and (c) are two metro maps while (b) and (d) are two overview maps.

Participants and tasks

We recruited four legally blind persons (two females, two males) aged between 31 and 65 years (M = 48.2, SD = 14.9). The study consisted in one training phase, one exploration task and one construction task using twelve Sucker pads and twelve Weights. During the training phase, participants were told how to construct a line by attaching two objects together. They could practice until they felt comfortable. Task 1 consisted in exploring one metro map and one overview map that had been previously made by the experimenter. Participants had respectively three and four minutes to explore those maps, and immediately after the exploration, they 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 Dycem sheet of paper, and one subject, who was not used to Dycem paper, used magnets on a board. Task 2 consisted in reconstructing two maps with the Tangible Reels, as quickly as possible. 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.

Experimental design

We used a within-subjects design with two independent variables for tasks 1 and 2 (Object design and Map):

- Object design (O). We evaluated the two object designs described below: the Sucker pads and the Weights.
- Map (M). For the exploration task we designed four maps (see Figure 4): two represented a part of a fictive metro map and required nine objects to be built and the other represented an overview map (inspired by Figure 2) and required twelve objects. For the construction task, we designed two other fictive metro maps (requiring nine objects) and two other overview maps (requiring twelve objects).

Procedure

The study was made up of two blocks corresponding to the two designs. A block consisted in training followed by the exploration task and finally the construction task. For both of these tasks a metro map was presented and then an overview map. After each task, participants answered a questionnaire. They also ranked the object designs according to their preference at the end of the session. The order of the blocks was counterbalanced among users. We also counterbalanced the two sets of maps, each containing two maps for the exploration and two maps for the construction.

Measures

For the exploration task, we measured the unintentional object displacement during exploration (distance in cm). In order to evaluate subjects' spatial learning, we presented the hand-drawn maps to four independent judges who were not involved in the project, alongside pictures of the maps that have been explored. The maps that were made with magnets (Participant 4) were thoroughly reproduced on a Dycem sheet. We asked the judges to evaluate the correctness of the drawn maps as 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. We had previously shown them three examples of drawings that should receive 0, 5 and 10.

Results

In this pre-study, we mainly focused on qualitative data. Participants are later referred as P1, P2, etc.

Objects Stability

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. During all the explorations, one Sucker pad got detached; none was moved. P1 almost knocked over three Weights, and P3 knocked over two Weights.

Map drawings and map construction

Figure 5 shows examples of drawings. 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 drawings (1.5 and 2.5). If we exclude her marks, the average mark for the overview maps was 7.0 (SD = 1.4). 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.

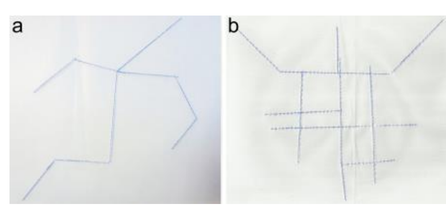

Figure 5: two drawings made after exploring the metro map (a) and the overview map (b) presented in Figure 4. They were respectively given a score of 8.6 and a 6.6.

Questionnaire and ranking

The participants specified on a 7-point Likert scale their level of agreement on a series of statements (1 = strongly disagree and 7 = strongly agree), for each task and each object design. The first four items were: *Building a map with these objects is: 1) pleasant; 2) difficult; 3) fast; 4) frustrating*. The last item was: 5) *it is easy to* *unintentionally move or knock over these objects.* For the exploration task, a sixth item was evaluated: "*these objects allowed me to understand the maps".* Table 1 shows the percentage of agreement for each statement.

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.

Task	Design	Pleasant	Difficult	Fast	Frustrating	Easy to knockover	Helpful
Exploration	Weights	25%	25%	50%	25%	50%	75%
	Sucker pads	100%	0%	50%	0%	0%	100%
Construction	Weights	75%	0%	100%	25%	50%	
	Sucker pads	100%	0%	75%	0%	0%	

Table 1. 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.

Qualitative feedback

Concerning the Weights, two participants stated that when they had to replace several objects it was easier to do with the Weights than the Sucker pads (P2, P4). P3 stated that as they could be easily moved, it was handy 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 not to 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 they were fewer risk to move them during the exploration (P1, P4). P4 also declared that "the advantage is that they do not take 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".

Conclusion to the pre-study

Both Tangible Reels proved to be easy to manipulate by a visually impaired user. Over the four Object Design * Tasks conditions, one participant only considered that building a map with the Tangible Reels was difficult while the majority found it pleasant. However, 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 positioning of the object is precisely guided before fixation. Several participants also reported that the height of the Weights hindered the exploration, and two participants knocked some Weights over. It is essential for the users not to be hindered by the objects when exploring or constructing a map. 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, even though we do not consider that Weights were not usable, 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 on 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.

STUDY: MAP CONSTRUCTION AND EXPLORATION

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. We used the apparatus described in the Implementation section above.

Participants

We recruited 8 legally blind persons (2 females, 6 males) aged between 24 and 65 (M = 43.8, SD = 14.4). Four 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.

Experimental design

We designed four maps of different complexities (see Figure 6) by gradually augmenting the number of points (6, 8, 10, 12), lines (5, 6, 7, 8) including oblique lines (1, 2, 3, 4), as well as crossings between lines (0, 2, 4, 6). Besides, 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. All points and lines were associated with a numerical label, ranging from 1 to 12.

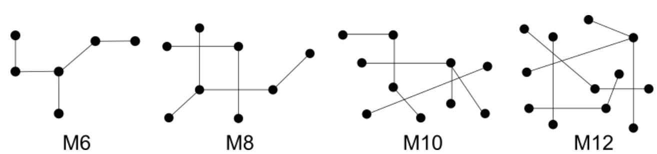

Figure 6: the four maps that the participants had to build using Tangible Reels. The complexity is increasing from left to right.

We used a within-subjects design with the Complexity of maps (four levels of complexity) as independent variable. All the participants had to construct the maps in the same order of increasing difficulty (M6, M8, M10 and M12).

Instructions and tasks

The study consisted in one familiarization phase followed by construction and exploration tasks with the Sucker pads. 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 made of five points.

After the familiarization phase, the participants built each of the four maps, and then answered 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 (see Figure 1c) and select the appropriate line and points before answering. During construction, when participants spent more than three minutes on one instruction, it was considered as a failure, and we provided help so that they could continue.

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 a SUS [3] and a NASA-TLX [5] 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.

Measures and statistical methods

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, from the first construction instruction until the object was correctly placed, and 3) time to answer each question. Effectiveness was assessed by the number of maps each participant successfully built and the number of correct answers to the questions. Satisfaction was measured using the SUS questionnaire and the participants' comments. During the construction, we logged successive positions of each Sucker pad being placed, as well as the occurrence of the different instructions. During exploration, we logged for each question the ID of the selected elements as well as the time at which they were selected. We therefore collected (6 + 8 + 10 + 12) * 8 participants = 288 trials for construction, and 4 maps * 3 questions * 8 participants = 96 trials for exploration.

We used the Shapiro-Wilk test to determine if the collected data followed a normal distribution. When distributions were normal, we computed a Univariate ANOVA test. Otherwise we used a Friedman test. Post-hoc tests were performed with the Wilcoxon Signed-Ranks Test for Paired Samples with a Benjamini and Hochberg correction.

Results

Construction

Twenty seven maps out of 32 were correct, which corresponded to 283 Sucker pads out of 288 (98.3%) correctly positioned and linked. Two maps were incorrect because one line did not start from the right Sucker pad (M6, M12), and three maps were considered incorrect because the participants required assistance from the experimenter (M8, M12, M12). Because the number of errors was very low (5) 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 the time, the user had moved away and therefore attached the new 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 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, he found the good Sucker pad to attach a new one, but did not wait enough to hear the feedback ("attached"), and then tried to attach it to other Sucker pads.

Figure 7 shows the average time to construct correct maps (not including 3 maps constructed with the help of the experimenter). A Friedman test showed a significant effect of Map Complexity on completion times ($\chi^2=16.4$, $p<.001$). Post-hoc pairwise comparison revealed significant completion time differences between M6 and M8, M10 and M12 ($p<.05$), between M12 and M8, and between M12 and M10 ($p< .05$).

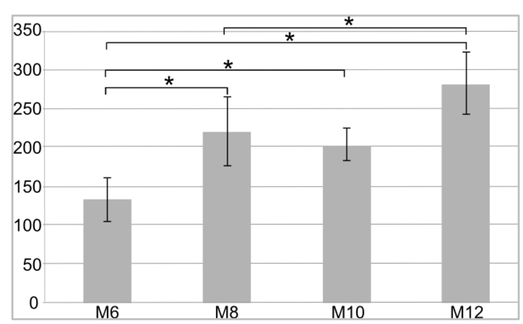

Figure 7: Average completion times (in seconds) to construct maps (error bars are IC95).

The average time to place a Tangible Reel was 23.7 on average. Post-hoc pairwise comparison revealed a significant difference in time needed to place a TR between M10 and M12 ($p<.05$). There was also a significant effect of Map Complexity on rough guidance time per object ($\chi^2=20.85$, $p<.001$). Post-hoc pairwise comparison revealed significant completion time differences between all the conditions ($p<.05$) as shown in Figure 8.

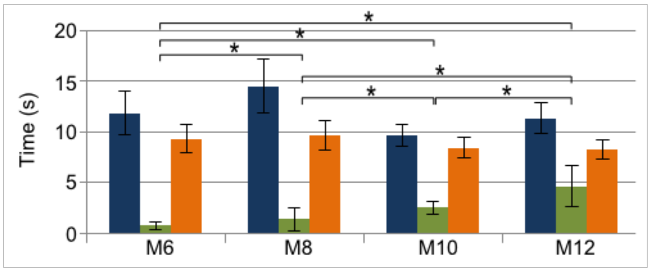

Figure 8. Average times and IC95 for the three steps required to correctly place a Tangible Reel: 1) attaching a Sucker pad to a previous one or placing it anywhere on the table (blue); 2) following rough guidance instructions (green); 3) following fine guidance instructions (orange).

Exploration

Table 2 indicates the average completion times, and the number of points and lines selected for each question (correct answers only). We found an interaction between Map Complexity and Number of elements selected (χ^2= 91, p=.01). Post-hoc pairwise comparison showed that participants selected less elements when exploring M6 as compared to M8, M10 and M12 (p<.05). Completion times to answer each question followed a normal distribution. An ANOVA with Map Complexity as factor showed that exploration times differed significantly ($F(3,28)=5.70$, p<.01). A post-hoc Tukey's HSD test indicated that exploration times for M12 were significantly higher than for M8 (p<.05) and M6 (*p*<.01).

	M6	M8	M10	M12
(a)	14.6 (11.1)	22.5 (17.7)	31.4 (23.9)	41.9 (27.8)
(b)	3.9 (0.9)	6.0 (1.0)	7.3 (2.0)	8.6 (0.8)

Table 2. Average time to answer one exploration question (a) and average number of elements selected (b). SDs are indicated in parenthesis.

The percentages of correct answers to the exploration questions were: 91.7% for M6; 95.8% for M8; 91.7% for M10, and 79.2% for M12. 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 to correctly perform the pointing gestures and therefore to select the lines (P3, P6).

Questionnaires

The average SUS score for the system was 83.6. Participants had to rate the difficulty of the task on a 7-point Likert scale (1 = very easy; 7 = very difficult). Figure 9 illustrates the number of participants who found the task rather easy (1, 2), normal (3, 4, 5) or difficult (6, 7). Table 3 indicates the scores of the NASA-TLX questionnaire.

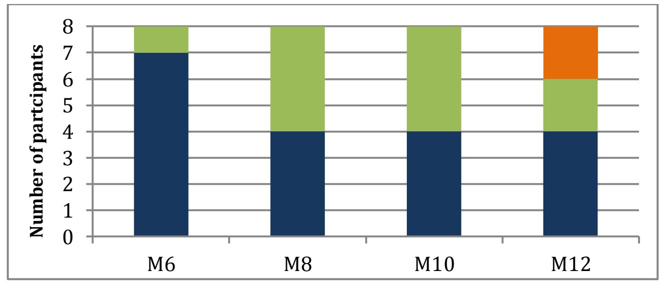

Figure 9: for each map, number of participants who found the task rather easy (blue); normal (green); difficult (orange).

Conclusions about map construction and exploration

Construction

Results shows that most of the participants managed to construct the maps without experiencing any usability issues. 85% of the maps were 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 constructing 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 did not keep on focusing on the instructions.

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 to perform pointing gestures with one finger only, and did not always manage to quickly select the lines and points. For example, P3 kept using several fingers and spent on average 8.7 seconds to select one element, whereas P7, who perfectly understood the gesture, spent only 0.96 seconds 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.

	<33	<66	<100
Mental demand	**62.5**	25	12.5
Physical demand	**75**	0	25
Temporal demand	**75**	25	0
Effort	**75**	25	0
Performance	0	12.5	**87.5**
Frustration	**75**	25	0

Table 3. For each NASA-TLX criteria, percentage of participants who indicated a value inferior to 33, 66 and 100.

Complexity

Four participants found that difficulty remained similar in the last three conditions (P1, P2, P4, and P5) or in the last two conditions (P4 and P7). The two participants who failed at reconstructing M12 found this task 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 will be too difficult to understand and explore more complex maps. It is interesting to note that except between M10 and M12, the completion times to place one object did not significantly increase 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 whole 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 statistical 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 increases as the map was being constructed (a Pearson correlation coefficient revealed a positive correlation : $r=0.64$, $p<0.01$). This probably reflects the time needed to find room where 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.

Satisfaction and usefulness

Overall, participants were highly satisfied with the performance (NASA-TLX score 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 construction, and two pinpointed 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 and mobility lessons).

DISCUSSION

Overall, we showed that Tangible Reels are efficient to materialize points and lines on tangible maps, and are easy to move and stable. A reel with strong magnets is used to link two or more phicons together and provide tangible lines. The pre-study showed that participants were able to easily manipulate Tangible Reels, and understand maps built with them. Results of the main study demonstrated that maps of different complexity are very often correct (85%) and can be explored by the users with accuracy (89.6% of correct answers). In addition, the system was efficient (23.7s only in average to place an object) and satisfying (SUS of 83.6). The exploration mode could be improved by allowing multiple fingers selection of points and lines, and providing specific feedback for lines crossings. However, several participants reported that Weights hindered map exploration, which suggests that the height of phicons should be carefully considered when they are used by visually impaired users.

Map complexity

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. When a larger amount of information is required, it would be interesting to materialize the most important elements using Tangible Reels, and then provide access to less important elements using gestural interactions as well as audio and haptic feedback (see [22] for instance).

Designing advanced functions

We designed a solution to make both points and lines tangible. Areas could also be represented and conveyed through audio (see [27] for example) or illusory tactile textures [6]. Besides, we started to design small objects (called "modifiers") that are attached to the strings and bend them to construct curves. Tangible Reels may also provide advanced functions like displaying/hiding particular points of interests, or zooming and panning. For example, for zooming, users will have to select the zoom mode, and move apart two objects. The digital map will be modified accordingly and the user will be guided to reposition Tangible Reels and place new ones.

More than tangible maps, tangible graphics

With the materialization of points and lines, we made it possible to construct maps. Obviously, Tangible Reels can potentially materialize any type of graphical representation including points, lines, and areas (graphs, flow charts, bar charts, etc.). Figure 10 illustrates three examples of graphical representations that a visually impaired person may access with Tangible Reels.

Figure 10. Other graphics with Tangible Reels

CONCLUSION

Graphics (maps, organigrams, bar charts, etc.) are widely used in education but also in everyday life. However technologies that help visually impaired users to perceive them are still uncommon. In this paper we introduced a tangible tabletop interface that allows building and exploring tangible graphics. More precisely, we described the design of Tangible Reels, a new type of phicons that can be used to materialize points and lines. We showed that they are stable, easy to manipulate, and can be used to convey spatial representations of different complexity.

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