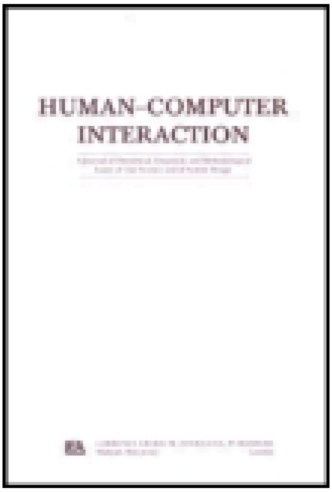

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Interactivity Improves Usability of Geographic Maps for Visually Impaired People

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Tactile relief maps are used by visually impaired people to acquire mental representation of space, but they retain important limitations (limited amount of information, braille text, etc.). Interactive maps may overcome these limitations. However, usability of these two types of maps has never been compared. It is then unknown whether interactive maps are equivalent or even better solutions than traditional raised-line maps. This study presents a comparison of usability of a classical raised-line map versus an interactive map composed of a multitouch screen, a raised-line overlay, and audio output. Both maps were tested by 24 blind participants. We measured usability as efficiency, effectiveness, and satisfaction. Our results show that replacing braille with simple audio-tactile interaction significantly improved efficiency and user satisfaction. Effectiveness was not related to the map type but depended on users' characteristics as well as the category of assessed spatial knowledge. Long-term evaluation of acquired spatial information revealed that maps, whether interactive or not, are useful to

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build robust survey-type mental representations in blind users. Altogether, these results are encouraging as they show that interactive maps are a good solution for improving map exploration and cognitive mapping in visually impaired people.

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1. INTRODUCTION

Mobility and orientation are among the biggest challenges for visually impaired people. More than half of the blind population in France reported that they face challenges regarding mobility and orientation (C2RP, 2005). Unfortunately, even if geographic information is available, it is often not accessible to the blind traveler. Internet and smartphones provide access to information and assisted navigation. Yet visually impaired people recently reported that this information was often not accessible to them (Banovic, Franz, Truong, Mankoff, & Dey, 2013). As a consequence, visually impaired people are not traveling at all or are, in the best cases, tied to previously learned routes, which has important consequences on professional and social life.

Travel preparation at home, in a safe environment, can provide visually impaired people with a mental representation (also called cognitive map) of the environment that they intend to visit and thus help to overcome fear related to traveling. Among other solutions, raised-line maps represent the environment and may enable visually impaired users to acquire spatial information (Jacobson, 1996). However, they present significant limitations. For instance, they provide a fixed, limited amount of information and require the use of a braille legend. New technology has opened up possibilities for designing accessible interactive maps (IM). These IM aim to overcome some of the limitations of classical embossed paper maps (PM). Landau and Wells (2003) argued that the combination of audio and tactile output enhances and facilitates learning as compared to purely tactile diagrams, which could be a motivation for schools and associations to buy and employ interactive technology in the education of visually impaired students. However, the usability of accessible IM has never been compared to the usability of classical raised-line maps. Therefore, designers and researchers miss the confirmation that IM do not raise accessibility or cognitive issues, and that they are equivalent or even better solutions than traditional embossed maps.

In the present study, 24 blind users explored an IM and a classical raised-line map. We then compared the three main components of usability for each map: effectiveness measured as spatial learning, efficiency measured as learning time, and satisfaction. In a follow-up experiment, we checked that spatial memory was not dependent on the type of map. We also observed the effect of time on memorization of spatial information as well as users' confidence in the acquired spatial knowledge.

1.1. Spatial Cognition, Maps, and Visual Impairment

Studying spatial cognition through map exploration requires the prior introduction of some notions. Siegel and White (1975) differentiated three types of spatial knowledge: landmark, route, and survey. They defined landmarks as specific geographic locations, strategic places to which a person travels. Examples of landmarks contain bus stops, public places, touristic sites, or shopping centers. Routes are then a second type of spatial knowledge, corresponding to an ordered sequence of landmarks. They usually represent familiar journeys. Typically route knowledge is enabling travel from the bus stop to the workplace. Finally, survey knowledge (also called configurational knowledge) corresponds to a maplike representation. It includes topographic properties of an environment, such as location and eventually distance of landmarks relative to each other or to a fixed coordinate system (Thorndyke & Hayes-Roth, 1982). As an example, a person would learn that the train station is located 500 m north of the town hall and that the museum is situated east of the town hall. These different types of knowledge are stored in mental representations through the integration of an ensemble of sensory and motor cues. It is possible to acquire these mental representations through direct experience of the environment, that is, navigation, as well as through verbal descriptions or exploration of physical representations—such as maps, photographs, or models (Gaunet & Briffault, 2005; Jacobson, 1996; Picard & Pry, 2009). Yet different sources lead to the acquisition of different types of spatial knowledge. Thorndyke and Hayes-Roth (1982) observed that route knowledge was normally derived from direct navigation. Although it is possible to acquire survey knowledge from direct experience, it can be obtained more quickly and with less effort from map reading (Thorndyke & Hayes-Roth, 1982). In addition, the quality of the representations is not equivalent. Survey knowledge is considered more flexible than route knowledge: When based on route knowledge, travelers are restricted to the routes they have previously memorized. In contrast, survey knowledge provides a global representation of an area and allows flexible alternation of travel (Jacobson, 1996). As a consequence, maps are an efficient mean for acquiring flexible and overall knowledge of an area. It has been shown that visually impaired people are able to acquire survey knowledge (see, e.g., Picard & Pry, 2009).

Maps as a Tool for Spatial Cognition

Maps are projective two-dimensional representations of a real space in smaller scale (Hatwell & Martinez-Sarrochi, 2003). They may have different geographical extents (anything from a room to a representation of the earth) and different contents (e.g., road network or demography). In this article we focus on orientation and mobility maps, which provide the possibility of exploring unknown areas, getting an overview about the surroundings of a landmark, localizing specific landmarks, or preparing travel (Heuten, Wichmann, & Boll, 2006). Maps also allow the absolute and relative localization of landmarks—such as streets or buildings—and the estimation of distances and directions. Maps have traditionally been hard-copy. With the rise of new technology, interactive and multimodal maps now exist on computers and smartphones. These maps provide new functions such as scrolling, zooming, and search functionalities. In addition map content can be dynamically updated and edited (e.g., in collaborative projects).

Maps for Visually Impaired People

When creating tools for visually impaired people, visual output has to be replaced by other modalities. Traditional maps for visually impaired people are tactile maps where different contents are presented in relief—that is, through raised lines—with the help of different lines, symbols, and textures (Edman, 1992). Braille is used to add textual information (Tatham, 1991). In several studies with visually impaired people, tactile maps have proved to be effective tools for acquiring survey knowledge (see, e.g., Ungar, 2000).

Although tactile maps are successfully employed, several limitations and problems are associated with them. First, tactile map reading is not innate and must be learned, as it implies several challenges for the inexperienced map reader (Hatwell & Martinez-Sarrochi, 2003). Touch is segmented and sequential, which places great demands on memory (Hatwell, 2003). Information has to be integrated from hand movements and cutaneous sensations from fingertips. Besides, the resolution of the finger is more limited than the resolution of the eye. Consequently, the design of a tactile map is challenging as it must contain only useful information (Hatwell & Martinez-Sarrochi, 2003). An excessively detailed map becomes cluttered and unreadable, and results in a perceptual overload for the reader (Jacobson, 1996). This is especially crucial when braille text is used. Braille needs a lot of space and is inflexible in size and orientation (Tatham, 1991). In order to avoid overloading the map, a legend is used to display braille text. The process of reading the legend, however, introduces disruptions in map exploration as the user has to alternate between reading the map and reading the legend (Hinton, 1993). Finally, another challenge is related to the fact that only a small part of the visually impaired population reads braille. A recent report states this number as low as 10% in the United States (National Federation of the Blind, 2009). In France 15% of blind people read braille and only 10% of them read and write it (C2RP, 2005).

As a response to these challenges, IM have the potential to provide a substantially broader spectrum of the visually impaired population with spatial knowledge, irrespective of age, visual impairment, skill level, or other considerations (Oviatt, 1997). In this regard, they appear to be an interesting means for providing visually impaired people with access to geospatial information.

1.2. Related Work

Interactive Maps for Visually Impaired People

The first IM was introduced by Parkes (1988). It was based on the idea of placing a tactile map overlay on a touch screen and augmenting the tactile map with audio output. Since this initial project, several new concepts of IM have emerged. The design of these maps differed in many aspects including content, devices, and interaction techniques. Brock, Oriola, Truillet, Jouffrais, and Picard (2013) presented an exhaustive review of these research projects. The vast majority represented geographic outdoor maps, and more precisely city maps (see, e.g., Miele, Landau, & Gilden, 2006). This makes sense as they directly respond to the need of visually impaired people to improve orientation knowledge. All these prototypes relied on touch as input modality—through the use of various devices—and only a few of them used speech recognition for the complementary access to additional information, such as distances, directions, or lists of on-screen or nearby targets (Kane, Morris, et al., 2011;

Simonnet, Jacobson, Vieilledent, & Tisseau, 2009). For output, all systems relied on some form of audio, either verbal through a TTS (text-to-speech synthesis) or through recorded speech (see, e.g., Kane, Morris, et al., 2011; Miele et al., 2006), or nonverbal through ambient sound, earcons, or music (see, e.g., Jacobson, 1998; Zhao, Plaisant, Shneiderman, & Lazar, 2008).

Brock et al. (2013) classified the prototypes according to the technology used to present map content. Haptic devices (i.e., mice, gamepads, and joysticks with force feedback) were used in many projects. The BATS project (Parente & Bishop, 2003) aimed to integrate low-cost consumer devices. Their prototype allowed a variety of devices capable of providing force feedback, including mice, trackballs, joysticks, and gamepads. Unfortunately haptic devices do not provide a fixed, reliable reference frame for exploration, and thus can make it difficult for visually impaired people to gather spatial information (Rice, Jacobson, Golledge, & Jones, 2005).

Another category included prototypes that rely on tactile actuator devices. These devices can produce tactile sensations such as relief, pressure, puncture, or friction (El Saddik, Orozco, Eid, & Cha, 2011) and thus reproduce local features of objects such as shape and texture. Most of these devices used a matrix of needles or pins that were mechanically moved up and down for displaying a map (Shimada et al., 2010; Zeng & Weber, 2010). However the rendering of information with raised-pin displays remains challenging as the resolution is quite low, in any case lower than the visual resolution of a normal screen. These raised-pin displays seem promising, especially if the display is large enough to be explored with both hands. However, they are very expensive (e.g., a 60 × 120 pin matrix cost €50,000 in 2012).

Touch-sensitive devices, including smartphones and touch tables, were most often used although they do not provide any tactile feedback to the user (Jacobson, 1998; Kane, Morris, et al., 2011). In some projects, the audio output was combined with tactile feedback such as vibrations (Poppinga, Magnusson, Pielot, & Rassmus-Gröhn, 2011; Yatani, Banovic, & Truong, 2012). Yet when vibrations are not spatially located, they proved to be less efficient than classical raised-line drawings for communicating graphical information (Giudice, Palani, Brenner, & Kramer, 2012). In line with the original idea proposed by Parkes (1988), it appears that the most usable IM prototypes rely on a raised-line overlay on a touch surface. For instance, Weir, Sizemore, Henderson, Chakraborty, and Lazar (2012) observed that users preferred exploring a sonified IM application when a raised-line overlay was placed on the touch screen. Likewise, it appears that touch screens become more efficient and effective to use with a raised-line overlay (McGookin, Brewster, & Jiang, 2008). Indeed, it is quite easy to augment raised-line documents with verbal and nonverbal audio. The idea behind this concept is to provide visually impaired map readers with a familiar interface, the tactile map that they learned to read at school. In addition this familiar interface can be augmented with interactive zones to provide more detailed information. This concept has been successfully employed in different research projects (see, e.g., Brock, Truillet, Oriola, Picard, & Jouffrais, 2012; Miele et al., 2006; Petrie et al., 1996; Wang, Li, Hedgpeth, & Haven, 2009).

Besides the research projects presented here, several commercial products slowly emerged. The iPhone and iPad provide the possibility to access map information with the default VoiceOver Screen Reader (http://www.apple.com/fr/accessibility/osx/voiceover/). The output is based on auditory feedback only, without any tactile cues. Ariadne GPS (http://www.ariadnegps.eu/) is a commercial map application for iPad or iPhone that goes further. It resembles the TouchOverMap project (Poppinga et al., 2011) in that the user receives audio and nonlocalized vibration feedback when moving the digit over the screen. Yet, without any tactile cues clearly representing the outlines of map elements, it is very difficult for the user to mentally integrate spatial shapes through hand movements. There are two commercial products that rely on touch surface with raised-line overlay. ABAplans (http://abaplans.eig.ch/index.html) is based on a mono-touch screen with map overlay and provides users with audio augmentation on certain elements. The second system, IVEO (http://www.viewplus.com/products/software/hands-on-learning/) by ViewPlus, also makes use of raised-line overlays on a monotouch screen. IVEO comes with many preprinted maps and software for drawing new ones. Even though these different systems are currently being launched on the market, it has never been shown that the usability is good or at least preserved when compared with regular embossed PM with braille legend.

Evaluating the Usability of Interactive Maps for Visually Impaired People

Usability is an important measure for evaluating interactive systems. It is defined as "the extent to which a system . . . can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (International Organization for Standardization, 2010). Although some studies have investigated the usability of interactive diagrams (Blenkhorn & Evans, 1998) or graphics (Giudice et al., 2012) for visually impaired people, there is still a need for studies on IM. Maps differ from other drawings in that they serve to present not only information (such as a list of elements) but also spatial configuration. For instance, Blenkhorn and Evans (1998) argued that schematic diagrams are different from maps because they explicitly show relationship between the parts of the diagram that are important, whereas in a map the relative position, shape, and size of elements must correspond to reality for the map to be meaningful. In addition, drawings usually refer to real objects that can be directly touched (e.g., a hammer), whereas maps refer to large-scale spaces that can be experienced only through navigation. Maps are really specific in that they must generate allocentric mental representations (survey knowledge) that will potentially be used in an egocentric perspective (route knowledge for navigation).

They are very few experimental papers presenting an IM prototype, which also include a user study. Often studies only report qualitative results (see, e.g., Parente & Bishop, 2003), and usability is not measured quantitatively regarding efficiency, effectiveness, and satisfaction or only some of these factors are measured. For instance, Landau and Wells (2003) studied satisfaction and effectiveness for an IM prototype but did not report efficiency. Furthermore, some prototypes were tested with blindfolded sighted participants instead of visually impaired people (see, e.g., Schmitz &

Ertl, 2010). This is problematic, as exploration strategies, mental representations of space, and use of interaction techniques differ depending on the visual capacities (Thinus-Blanc & Gaunet, 1997). Although it appears crucial, no prior study compared the usability of an IM with the usability of a classical raised-line map for visually impaired people. If IM were less efficient, less effective, or less satisfying than raised-line maps, the use of advanced interactive devices for visually impaired people should be questioned. The design of new types of interaction is not justified if usability is not guaranteed. In this case, designing IM should focus on usability first, and it should be ensured that appropriate methods are used for evaluation. On the contrary, if it were observed that IM were equivalent or even better solutions than regular embossed maps, researchers and designers would know that IM do not raise accessibility or cognitive issues, and that making use of interactivity can improve accessibility for visually impaired people.

Consequently, the objective of the present study was to compare the usability of a PM versus an IM for learning a neighborhood. In a follow-up study, we also checked the effect of time (delay of 2 weeks) on the memorization of the elements and the global configuration of the map. We introduced a method including the three usability factors (effectiveness, efficiency, and satisfaction). Our results show that replacing the braille legend by simple touch and audio interaction significantly improved exploration times (efficiency) and user satisfaction. Concerning effectiveness, measured as spatial cognition scores, we observed that improvement in spatial learning and memorization depended not on interactivity but on users (e.g., expertise with tactile map reading) as well as the type of spatial knowledge (landmark, route, survey). Furthermore, we observed that maps in general, independently of interactivity, are an important means for improving configurational and robust spatial knowledge in visually impaired people. Our results also suggest that interactivity can provide the early blind and those who are not braille readers with a chance to improve space-related knowledge. These results are encouraging as they show that IM are a usable solution for making geographic maps accessible to visually impaired people.

2. MATERIAL AND METHODS

In this study we compared the usability of a raised-line PM and an IM. The users were legally blind and the context of use was map reading. Our general hypothesis was that an IM was more usable than a tactile PM for providing blind people with spatial knowledge about a novel environment. We made the following specific predictions concerning the three usability factors:

1. Efficiency: We predicted a shorter exploration time devoted to map learning for IM than for PM. This reasoning was based on the fact that PM was accompanied by a legend. The alternation between map reading and legend reading introduces a disruption which does not exist with the IM (Hinton, 1993).

2. Effectiveness: We predicted that participants would acquire more accurate and reliable spatial knowledge with IM than with PM. This is based on the assumption that multimodal output is more beneficial than using one modality alone. For instance, when comparing the use of a touch screen-based system with audio output and with or without raised-line overlay by visually impaired people, users made fewer errors and were quicker when using the interface with the overlay (McGookin et al., 2008). We observed the different types of spatial knowledge (landmark, route, and survey) after map exploration. We made the predictions that spatial scores and confidence would be improved when using IM. We also predicted that this advantage related to IM would be preserved 2 weeks after map exploration.
3. Satisfaction: We predicted that IM would yield higher satisfaction scores—that is, positive attitudes toward the use of the map—than PM. Previous studies observed a high satisfaction rate when visually impaired people used interactive devices (see, e.g., Kane, Morris, et al., 2011). We made the assumption that users would perceive the IM as more accessible and ludic. We also hypothesized that users who encounter difficulties with braille reading would prefer audio output.

In a follow-up experiment, we observed the effect of time and map type on memorization of spatial information, as well as users' confidence in the acquired spatial knowledge.

The following sections present the design of the maps and interactions used in the experiment, as well as the protocol, participants and observed variables.

2.1. Material

We tested the same raised-line maps under two different conditions ("map type"): the PM condition corresponded to a regular raised-line map with braille legend, and the IM condition corresponded to a touch screen with a raised-line map overlay (without any braille text) and audio feedback. We designed two different but equivalent contents to counterbalance the putative effects of map content (1 and then 2, or vice versa) and condition order (PM and then IM, or vice versa).

Design Choice

As mentioned in the introduction, the design space for accessible IM is large and heterogeneous (Brock et al., 2013). Current IM prototypes vary in many aspects, including map content, devices, and interaction techniques. Several advantages and disadvantages exist for the different types of IM, and it is impossible to identify "the best solution" as this depends on context, task, user preferences, and so on. Our aim was to develop a prototype that allows a visually impaired person to explore an unknown geographic area at home, at school, or in another static context. The exploration of this map must allow the user to acquire spatial knowledge concerning a specific neighborhood (e.g., around a point of interest). In this study we designed an IM prototype based on a multitouch surface, a raised-line map overlay representing a neighborhood, and audio output. This prototype is consistent with the IM initially proposed by Parkes (1988). The choice to remove braille is also consistent as only a small percentage of the blind population reads braille (National Federation of the Blind, 2009). However, in contrast to other studies our prototype relies on a more recent multitouch surface that allows regular two-handed exploration strategies, as well as the potential design of advanced interaction gestures.

The Interactive Map Prototype

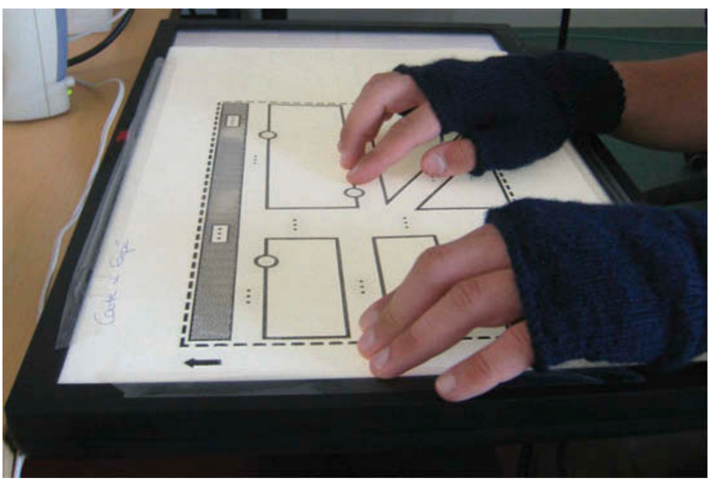
Choice of Multitouch Surface. All applications were developed on a HP EliteBook 8530p connected to a multitouch device. We identified some criteria to choose the multitouch surface (Brock, Truillet, Oriola, & Jouffrais, 2010). The most important one was the compatibility with a paper overlay, meaning that touch input was still recognized with the overlay placed on top of the surface. The second criterion was the number of touch inputs. As visually impaired people usually explore tactile maps with both hands and multiple fingers (Wijntjes, van Lienen, Verstijnen, & Kappers, 2008), a multitouch surface with at least 10 touch inputs permits people to track and register finger movements during map exploration. Concerning the size, Tatham (1991) proposed that maps for visually impaired people should not exceed two hand spans (450 mm). This size allows using one of the fingers as anchor point to put other map elements in relation to the current one regarding distance and direction. Obviously, it is challenging to memorize large-scale maps, and it is difficult to present tactile maps in a very small format—for example, the size of a smartphone screen. During pretests with different map sizes we observed that the size should be at least A4 format and that users preferred maps in A3 format. To preserve map reading habits and comfort of blind users, we set up our map in a horizontal plane and with the landscape orientation.

The multitouch surface used in the current study was the 3M Inc. M2256PW. The projected technology preserved responsiveness through the paper overlay. The dimensions of the screen (slightly larger than A3 format) were well adapted for representing a city neighborhood. Finally, it provided real multitouch capacity with up to 20 touch inputs.

Software Architecture. Our IM prototype was based on a modular software architecture in which different modules (i.e., applications) were connected via a software bus (Buisson et al., 2002). The first module detected touch input. We used the surface low-level driver to get ID, coordinates, and timestamp for each touch input. This information was sent to the second module, which displayed map content, and determined the map element being touched. The third module received messages from both other modules and implemented the state machine to differentiate interaction from exploratory movements. Finally, this module sent the text output message to a text-to-speech (TTS) module using Microsoft Speech Application Programming Interface version 4. It is worth noticing the versatility of this type of modular prototype for experimenting with different configurations.

Touch Input. The objective of the state machine was to differentiate exploratory finger movements (i.e., following the raised-lines) from touch interaction (i.e., touching the screen to obtain information). We tested different types of touch input. In a first version we implemented a single tap interaction. Although the single tap worked fine with sighted users, it did not work with blind users. Indeed visually impaired users explore tactile maps with several fingers, which triggered many simultaneous sound outputs. The blind users who tested the system were then not able to understand which finger caused sound outputs. Similarly, McGookin et al. (2008) observed accidental speech output for single tap interaction. As we wanted to preserve natural two-hand exploration, we looked for alternative touch inputs that would unlikely trigger events by chance. Kane, Wobbrock, and Ladner (2011) identified double taps as gestures that are usable by blind people. Multiple tap interaction was also used in the Talking TMAP project (Miele et al., 2006) and by Senette, Buzzi, Buzzi, Leporini, and Martusciello (2013). We therefore used a double tap technique with a 700-ms delay between two taps. The standard speed for mouse double clicks in Microsoft Windows Operating System, which is 500 ms, proved to be too short. The double tap ended right after the second tap, whereas the digit was still touching the surface. This allowed the user to keep the tapping finger on the IM element that was selected. Pretests showed that this double tap technique was efficient and was more natural for visually impaired users. However, a few unintended double taps still occurred, mainly because of the palms of the hand resting on the map during exploration (as discussed by Buxton, 2007). We therefore asked users to wear mittens during map exploration, which minimized the occurrence of unintended touch inputs (Figure 1[1]).

FIGURE 1. Photograph of a user exploring an interactive map.



***Note.* The raised-line map overlay is attached on top of the touch screen. The user is wearing mittens to prevent unintended touch input from the palms.**

1. Explanations of the diagrams for visually impaired readers are included as supplementary material.

Speech Output. In the experimental prototype, speech output announced the names of streets and points of interest. We used TTS because synthesized speech is more flexible than recorded speech. We opted for the RealSpeak SAPI 4.0 TTS with the French female voice "Sophie" for its good intelligibility and user satisfaction (Côté-Giroux et al., 2011). It was important that users perceived the TTS as comfortable regarding volume, pace, and voice. Although blind users are used to screen readers at a high pace (Asakawa, Takagi, Ino, & Ifukube, 2003), we implemented a standard pace. We wanted to make sure that users would understand single unknown words, even out of context, and with a nonfamiliar voice. Speakers were connected to the computer. The volume of the speech output was kept constant at an audible level during the whole experiment.

Raised-Line Map Design

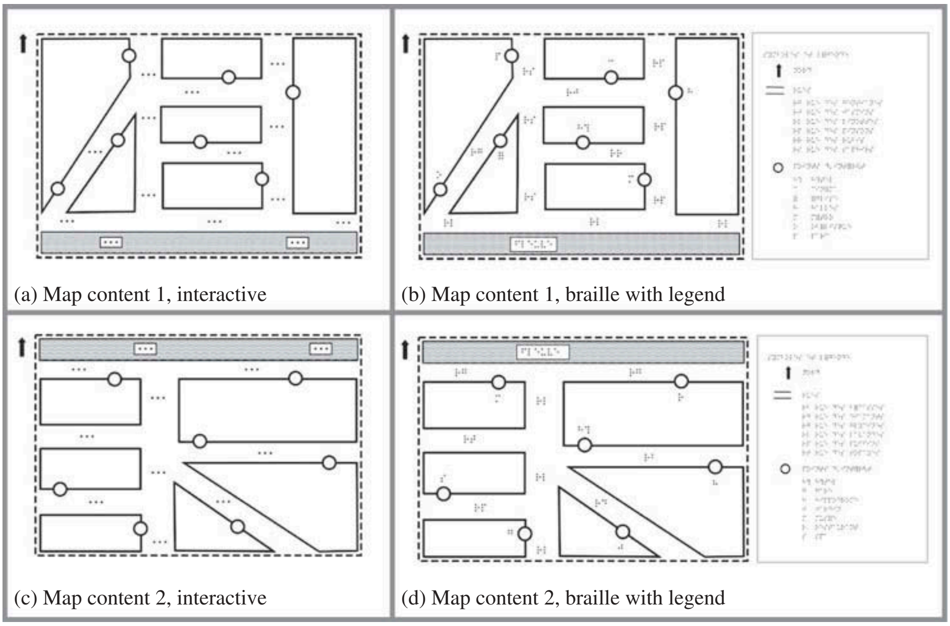
Raised-line maps use different symbols and textures, without obeying any strict design recommendations. Nevertheless, tactile symbols must respect minimal sizes and distances in order to be perceivable (Tatham, 1991). Edman (1992) presented a comprehensive summary on the guidelines for tactile map and image design. During the design of our raised-line maps we respected the guidelines as described by Picard (2012). A dashed line (line width 1.4 mm; miter join; miter limit 4.1; butt cap; no start, mid or end markers) presented the outer limits of the map. Streets and buildings were separated by a solid line (line width 1.4 mm; miter join; miter limit 4.0; butt cap; no start, mid or end markers). A texture represented a river (texture "wavy"). Points of interests were represented by circles (width and height 12.4 mm, line width 1.4 mm). An arrow on the left upper side of the map indicated the north direction.

The maps were designed with the Open Source Inkscape software (http://inkscape.org/) in SVG (Scalable Vector Graphics) format (http://www.w3.org/Graphics/SVG/). SVG is an XML based format convenient to provide both a topographic view of a geographical place and a textual description of the included elements. Many projects use the SVG format for the design of IM (see, e.g., Miele et al., 2006).

We designed a first map representing a fictional city center with six streets, six buildings, six points of interest (e.g., museum, restaurant, and public transport) as well as one geographic element (a river). A second map was then created with the same map elements that were rotated and translated, so that both map contents were equivalent. A central point of interest in the middle of the map (hotel) was common for both maps (see Figure 2). We have made the choice to design maps with low complexity and a limited number of elements to make sure that users could read and memorize the map content within a reasonable amount of time. Both map contents were then produced with or without braille. Pretests with a visually impaired user ensured that the maps were readable and that they were not too easy or too difficult to memorize.

We also assured the lexical equivalence between maps by means of the "Lexique" database (New, Pallier, Ferrand, & Matos, 2001). We considered two criteria for inclusion of equivalent text: the frequency of oral usage (number of occurrences per million in subtitles of current movies) and the number of syllables. These criteria are important

FIGURE 2. Four different variants of the map existed in total.



***Note.* Two different map contents are depicted in (a, b) and (c, d). They are based on the same geographic elements, which were rotated and translated. Both map contents existed with braille (b, d) and in interactive format (a, c). Circles are points of interest (either the points were interactive or accompanied by a braille abbreviation). The marks composed by three dots are interactive elements to access street names.**

because more frequent words and shorter words are usually easier to memorize. Another constraint was that words had to begin with different letters so that each braille abbreviation was unique. All street names were composed of two syllables and were low frequency words, that is, words with less than 20 occurrences per million. In addition we used categories for the names: On each map two streets were named after birds, two after precious stones, and two after flowers. On each map there were six points of interest (POI) with counterbalanced frequencies and number of syllables. In addition to these six POIs, we added a reference point on both maps, which was the hotel. The word "hotel" had the highest usage frequency among all POIs that we selected.

Specificity for the Raised-Line Map With Braille Legend (PM). In regular raised-line maps, braille legends provide information on the different map elements. Legends are usually based on numbers or abbreviations positioned close to the elements that they describe. These markers are then found in the legend section with additional textual information. We used abbreviations rather than numbers as they facilitate the cognitive association with the full name of the element. All street name legends began with the word rue (French translation for "street") followed by the name of the street. The corresponding abbreviation was the letter "r" followed by the initial of the street name.

For example "rue des saphirs" (Sapphire street) was abbreviated "rs" (Note that in French, an article between both words is required). POIs were abbreviated with the initial of their name (e.g., "museum" was abbreviated with the letter "m"). The braille legend was printed on a separate A4 sheet of paper that was placed next to the map (see Figure 2). Text was written in uncontracted braille with the font "Braillenew" (font size 32 and line spacing 125%).

Specificity for the IM. The IM included particular zones and elements that were interactive; a double tap on these elements provided their name (see Figure 2). Street names were marked with three dots (font DejaVuSans, normal, font size 47.5, line spacing 125%). These marks were repeated between crossings of the same street to avoid ambiguity. The circles representing POIs were made interactive without any additional mark (the name of the POI was announced on double tap on the circle).

Map Printing. The two main methods used for printing raised-line maps are vacuum forming and microcapsule paper (Edman, 1992). Perkins (2001) showed that both techniques were efficient for presenting spatial information. We chose microcapsule paper because it is easier to handle. Another important aspect was that this kind of paper is slimmer, which is advantageous to detect touch input through the PM. We used A3 format swell paper of the brand ZY®-TEX2. Maps were printed in landscape format with a Toshiba e-STUDIO 355 copier. For the braille legend we used A4 paper printed in portrait format with a Dell 3330dn Laser Printer XL. In both cases we used the same Piaf fuser for creating the relief. Embossment of microcapsule PM is altered after several uses. Therefore, we printed out a new exemplar after the map had been used five times. We checked that this was sufficient to maintain quality and readability of the maps over the whole experiment.

Experimental Setup

To sum up, the IM prototype in our study was composed of a raised-line PM placed over a multitouch screen, two loudspeakers, and a computer on which the map application was running (Figure 1). The IM prototype was functionally comparable to a regular tactile PM. Users could explore the raised-line map on top of the screen with both hands, that is, 10 fingers, exactly the same way that they would explore a PM. Exploratory movements did not produce any speech output. The IM contained no legend; braille was replaced by audio output that was triggered through a double tap on the markers. No further input or output interaction was provided to ensure functional equivalence with the PM. The raised-line map overlay in the interactive prototype was identical to the raised-line map in the paper condition, except for the marks (braille abbreviation vs. three dots) and absence of legend.

2.2. Participants

Participants were recruited among students and employees of the Institute of the Young Blind Toulouse (Institut des Jeunes Aveugles, CESDV- IJA), among the user group of the Navig project (Katz et al., 2012), through announcement in the newsletter of the Valentin Haüy association, through a local radio broadcast for visually impaired people as well as by word of mouth. All participants gave informed consent to participate in the whole experiment composed by four sessions interleaved with 1 week. They received a gift certificate after completion of the study. None of the participants had seen or felt the experimental setup or been informed about the experimental purposes before the experiment. To access users' characteristics we used interviews instead of questionnaires, following our previous recommendations for participatory design with visually impaired people (Brock, Vinot, et al., 2010).

Figure 3 shows the personal characteristics of the 24 legally blind participants (12 women, 12 men). Chronological age varied from 21 to 64 years (*M* chronological age = 42 years, *SD* = 13.15). The age at onset of blindness varied from 0 to 27 (*M* value = 8.71, *SD* = 8.51). The proportion of lifetime without visual experience (Lebaz, Picard, & Jouffrais, 2010) varied from 0.24 (meaning that the participant spent 24% of his life without visual experience) to 1 (meaning that the participant was born blind). The mean value was 0.87 (*SD* = 0.23). The blindness had different etiologies, including

FIGURE 3. Description of the visually impaired participants.

Subject	Gender	Chronological age (yrs)	Age at onset of blindness (yrs)*	Etiology of blindness	Occupation
1	F	31	2	iritis	lawyer, certified public accountant
2	F	58	0-15	congenital	administrative occupation
3	M	25	0	optical neuritis	student (communication technologies)
4	M	21	14-15	infectious disease	student (languages)
5	F	33	25-27	retinitis pigmentosa	front office employee (in training)
6	M	53	0-19	infectious disease	furniture manufacturer
7	M	31	5	accident	furniture manufacturer
8	F	54	0	optic atrophy	teacher (Braille)
9	F	38	0	retinitis pigmentosa	front office employee (unemployed)
10	F	64	0-10	genetic disease	retired physiotherapist
11	M	48	25	accident	physiotherapist
12	M	59	0	retrolental fibroplasia	teacher (computer science)
13	F	42	0-15	genetic disease	beautician
14	M	62	5	congenital	retired engineer
15	F	51	6	retinoblastoma	teacher (mathematics)
16	M	51	0	retrolental fibroplasia	telephone operator
17	F	58	0	genetic disease	retired teacher (Braille)
18	M	25	0-1	genetic disease	assistant secretary (in training)
19	M	33	0-14	glaucoma	translator (in search for a job)
20	F	36	0-12	glaucoma	front office employee (in training)
21	M	31	0-19	glaucoma	songwriter, pianist
22	F	41	0	retrolental fibroplasia	teacher (music)
23	F	27	13	retinal detachment	teacher (Braille)
24	M	39	6	infectious disease	software developer

***Note.* Means and standard deviations have been omitted from this table. *When visual impairment was progressive, two values are reported (the second value indicates the age at which legal blindness occurred).**

different illnesses as well as accidents. Some participants could perceive light or large objects when being very close but denied being able to use this residual vision in any form of spatial behavior. None of the participants had a known neurological or motor dysfunction in association with the visual impairment.

We observed several personal characteristics including age, use of innovative technology, braille reading skills, tactile image reading skills, and orientation skills. For the subjective estimation of braille reading, tactile image reading, and use of innovative technology we used a scale of 1 (*low*) to 5 (*high*). All participants were braille readers as this was a crucial condition to participate in the study. Braille reading experience varied from 5 to 58 years ($M = 32$ years, $SD = 14.8$). Most subjects read braille bimanually. We also assessed braille reading expertise ($M = 4$, $SD = 1.0$). We examined expertise of reading tactile images ($M = 3.3$, $SD = 1.1$)—including figurative images, maps, and diagrams. All users except one had prior experience in reading tactile images. We also assessed frequency of using new technology ($M = 4.2$, $SD = 0.9$) as well as users' expertise regarding new technology ($M = 4$, $SD = 0.9$). All participants had regular access to a computer and a cell phone. Most users also possessed a MP3 player. Proportion of lifetime with blindness was correlated with the frequency of using new technology (NewTech_freq; see Figure 8), meaning that early blind people were frequent users of new technology.

As this study focuses on exploration and learning of topological maps, we were also interested in participants' mobility and orientation skills. Participants' orientation skills were examined using the Santa Barbara Sense Of Direction Scale (SBSOD; Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002), which we translated into French. Besides we adapted the SBSOD to the context of visual impairment. Question 5 ("I tend to think of my environment in terms of cardinal directions") had been extended to "I tend to think of my environment in terms of cardinal directions (N, S, E, W) or in terms of a clock face." This modification has been proposed because the clock face method—that is, indicating straight ahead as noon, to the right as 3 o'clock, and so on—is a popular method for orientation among the visually impaired population. Question 10 ("I don't remember routes very well while riding as a passenger in a car.") was changed to "I do not remember routes very well when I am accompanied." Scores from the SBSOD obtained a mean of 5.2 ($SD = 0.6$). We also interviewed users on their ease of travel ($M = 4.1$, $SD = 0.9$) on a scale of 1 (*low*) to 5 (*high*). Ease of travel was negatively correlated with proportion of lifetime with blindness and age (see Figure 8), meaning that older and early blind people faced more apprehension toward traveling.

It is important to note that our subjects evaluated themselves as being above average concerning mobility and orientation. The SBSOD has been used in studies with sighted people (Hegarty et al., 2002; Ishikawaa, Fujiwarab, Imaic, & Okabec, 2008) and has never been as high as in our study. A possible explanation is that visually impaired people who volunteer for a study concerning mobility and orientation are highly autonomous—they have to travel to the lab—and feel proud and confident regarding traveling.

2.3. Procedure

In the following section, we describe the familiarization phase and the main experiment that was composed of a short-term and a long-term study.

Familiarization Phase

The experiment included a familiarization phase so that participants could get used to the map presentation and interaction. For this phase, we designed a simplified map containing only four streets and four POI. We chose abstract names—streets and POIs were numbered (Street 1 to Street 4 and POI 1 to POI 4)—to avoid confusion with the experimental map. The subjects were encouraged to explore the familiarization map that was presented as either a paper or interactive version. All but one subject were already familiar with reading tactile PM. Thus, the familiarization phase for the braille map mainly served to ensure the subjects were aware of the symbols and textures used on our maps. In contrast, the IM was unknown for all users. They had to master the double tap to activate the interactive elements and to become familiar with the speech output. Familiarization time was limited to 10 min but users were free to stop earlier if they felt comfortable with the map. The time limit was sufficient for all participants.

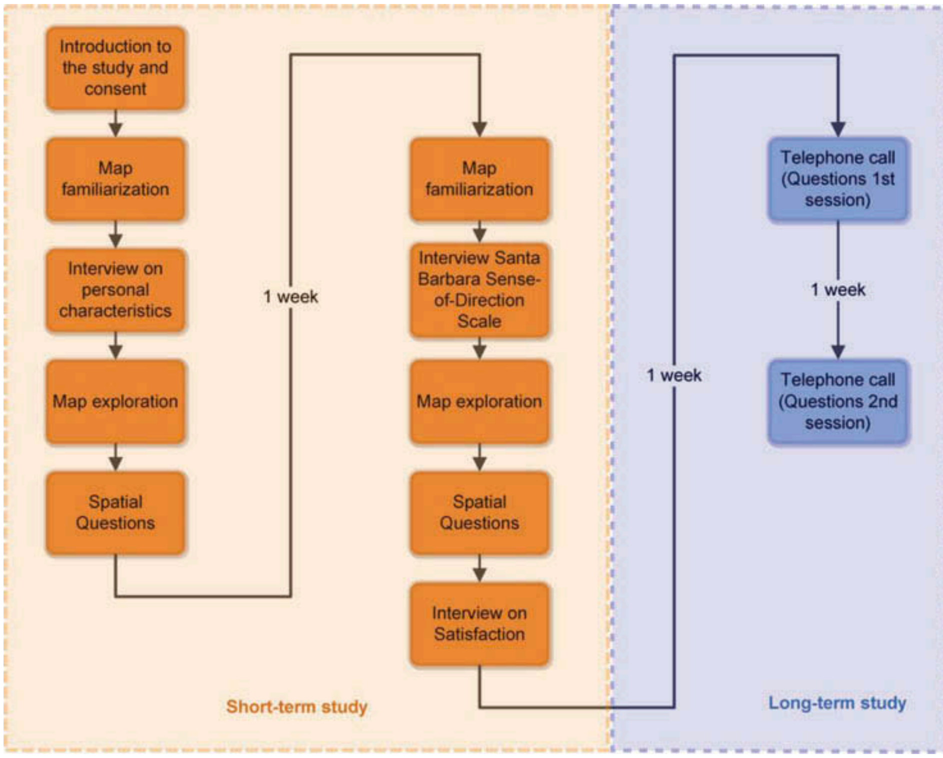
Protocol

The experimental protocol included a short- and a long-term study that were each composed by two sessions (see Figure 4). To avoid confusion between the different map contents, we decided to split the evaluation into separate sessions. We fixed a delay of 1 week between each of the four sessions, so that it took 3 weeks for each participant to complete the whole experiment. This time schedule was imposed by the fact that we wanted to evaluate both short- and long-term memory for spatial memorization. The delay of 1 week between the sessions for each map was set to 1 week for a practical reason: Users could select a weekday that was convenient for them.

Short-Term Study: Comparison of the Usability of Different Map Types

The two sessions of the short-term study took place in the laboratory ULYSS, a dedicated experimental environment in the IRIT research laboratory. Transport was organized door to door using the "Tisseo Mobibus service," a local transportation service for people with special needs. Alternatively if participants preferred using public transport, they were picked up at the nearest metro or bus station and then accompanied to the laboratory. Video and sound files were recorded for both sessions after agreement from the participants. The mean duration of these sessions from arrival in the experimentation room to the end of the session without waiting for transport was 56.7 min ($SD = 16.3$). The minimum time was 30 min and the maximum time was 103 min. There was no significant time difference between the two sessions.

FIGURE 4. Experimental design of the study.



Note. **The experiment was composed by a short-term and a long-term study. In this article the color code orange will be used for the short-term and blue for the long-term study.**

Both sessions were organized following a similar procedure. In the first session, the subjects explored the familiarization map. Following this, an interview on personal characteristics was conducted. Then, we asked subjects to explore and learn the first map (either IM or PM depending on the group) with both accuracy and time constraints ("as quickly and as accurate as possible"). Participants were informed that they would have to answer questions afterward without having access to the map. To motivate them to memorize the map, we prepared a scenario: Users were asked to prepare holidays in an unknown city, and we invited them to memorize the map in order to fully enjoy the trip. Magliano, Cohen, Allen, and Rodrigue (1995) observed that subjects remembered different types of map knowledge (landmark, route, or survey knowledge) depending on the instruction before exploration. Thus, to motivate users to memorize all types of spatial information, we did not provide any cue on the kind of map knowledge that they should retain. Subjects were free to explore until they felt like they had memorized the map. When they stopped, we measured the learning time and removed the map. Subjects then answered a questionnaire for assessing the three types of spatial learning (landmark, route, survey).

The second session took place 1 week later and started with a familiarization phase followed by an interview on the SBSOD Scale. The subjects then explored the second map type (either PM or IM depending on the group of subjects) and responded to the questions on spatial knowledge. We finally assessed their satisfaction regarding the two different map types with the System Usability Scale (SUS) questionnaire (Brooke, 1996) translated into French. After the questionnaire, we asked users which aspects they had liked and disliked about the two map prototypes. Part of the results on satisfaction has been published in Brock et al. (2012).

Long-Term Study: Investigating the Map Types' Effect on Spatial Memory

The long-term study extended the short-term study by two telephone interviews. The first phone call took place 2 weeks after exploration of the first map, and users were asked the same spatial questions as during the first session. They were previously informed about the phone call but not about the nature of the questions. The second phone call took place 2 weeks after the second map exploration, and users were asked the same questions as in this second session. Phone interviews lasted between 10 and 15 min.

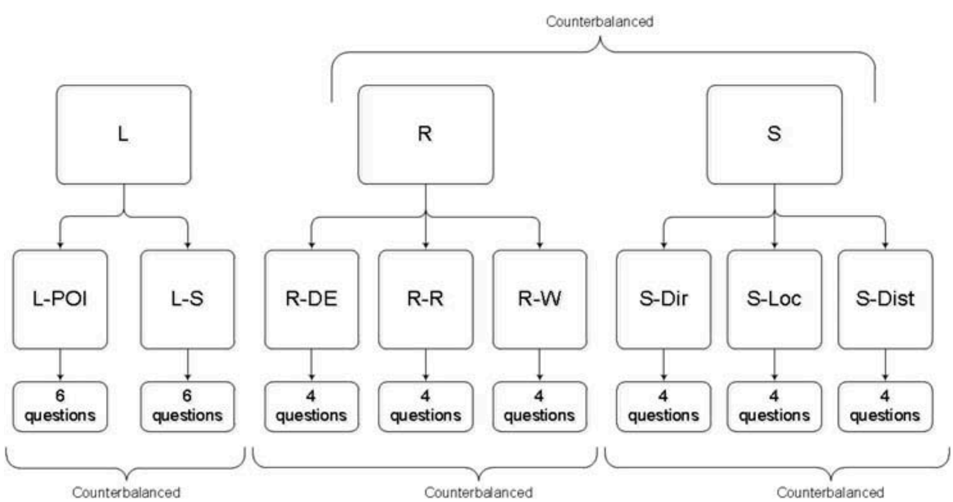
Observed Variables and Statistics

The principal independent variable in our study was the map type. Participants were divided into two groups in which the order of presentation of the two map types was counterbalanced (PM first and then IM, and vice versa). We did not expect the map content to have any effect on the results. Nevertheless, to assure correctness of the results, the order of presentation of the two different—but equivalent—map contents (1 and 2) was counterbalanced. The experience was therefore based on four groups with the following conditions: PM1-IM2, PM2-IM1, IM1-PM2, and IM2-PM1.

We measured usability through the three factors effectiveness, efficiency and satisfaction. Efficiency was measured as learning time, that is, the time needed for acquiring map knowledge. Satisfaction was evaluated with the SUS questionnaire (Brooke, 1996) as well as qualitative questions. As proposed by Bangor, Kortum, and Miller (2008) we replaced the word "cumbersome" with "awkward" to make Question 8 of the SUS easier to understand. In an earlier study we had observed negative reactions to Question 7, which is entitled "I would imagine that most people would learn to use this product very quickly." Users had stated that "most people" would not use a product for visually impaired people. Therefore, we changed the wording to "I think that most visually impaired people would learn to use this product very quickly." Finally, effectiveness was measured with spatial questions. More specifically we wanted to assess the three types of spatial knowledge: landmark, route, and survey (Siegel & White, 1975). There is a variety of methods to evaluate spatial cognition, but they are not all adapted to visually impaired subjects. We followed the suggestions from Kitchin and Jacobson (1997). We prepared several types of questions related to the same type of knowledge, which provides subjects with the chance to compensate for shortcomings on one specific type of question. For instance, one series of questions relied on the clock face method, whereas another series relied on cardinal directions. This example is substantial as some blind people are used to the clock face method, whereas others prefer using cardinal directions to orient themselves. For assessing the landmark knowledge we asked participants to list the six street names (task called "L-S") and the six points of interest ("L-POI") presented on the map. The order of L-S and L-POI questions was counterbalanced across subjects. After completion of the landmark (L) related questions, we read out the complete list of streets and POI without giving any information concerning their locations on the map. This was to avoid that failure in the subsequent route and survey tests were due to failure in short-term memory. Questions related to route (R) and survey (S) knowledge were each divided into three blocks of four questions. The order of presentation of route and survey questions as well as the order of presentation of the blocks within each question type was counterbalanced, but the order of the four questions within each block was maintained. Figure 5 depicts the structure of the questions.

The three blocks for R type questions (containing each four questions) were (a) Route distance estimation ("R-DE"): Two pairs of POI were proposed (e.g., museum - spa vs. railway station - obelisk), and participants had to select the two points separated by the longest route when following the roads (also called functional distance by Ungar, 2000); (b) Route recognition ("R-R"): A route between two points was described and participants had to decide whether the description was correct; and (c) Wayfinding ("R-W"): A starting point and a destination were provided. Then the participants had to describe the shortest route between these two points.

FIGURE 5. Structure of the spatial questions in the study.



***Note.* Questions were separated in three categories: landmark, route and survey. Within each category questions were counterbalanced. L = landmark; L-POI = landmark-points of interest; L-S = landmark - street names; R = route; R-DE = route distance estimation; R-R = route recognition; R-W = route wayfinding; S = survey; S-Dir = survey direction estimation; S-Loc = survey location estimation; S-Dist = survey distance estimation.**

The three blocks for S-type questions (containing each four questions) were (a) Direction estimation ("S-Dir"): A starting point and a goal were given, and participants had to indicate the direction to the goal using a clock face system (e.g., three o'clock for direction east); (b) Location estimation ("S-Loc"): The map was divided into four equivalent parts (northeast, northwest, southeast, southwest), and participants had to decide for a POI in which part it was located; and (c) Survey distance estimation ("S-Dist"): Two pairs of POI were proposed (e.g., museum - railway station vs. spa - obelisk), and participants had to decide which distance was the longest one in a straight line (Euclidian distance).

Over the whole test each subject could get a maximum of 36 correct answers (12 for L, 12 for R, and 12 for S). The spatial scores were compared regarding map type (within-participant factor), order of presentation (between-participant factor), and spatial task (within-participant factor). For the long-term study the time was introduced as a within-participants factor.

Finally, we introduced another set of dependent variables: the users' confidence in their responses to spatial questions. We let participants evaluate confidence on a scale from 1 (*not confident at all*) to 5 (*very confident*). The question was systematically asked after each of the eight blocks of spatial questions. We tested if confidence was dependent on the map type, order of presentation, and the type of spatial knowledge, as well as the delay between exploration and questions (short term vs. long term).

3. RESULTS

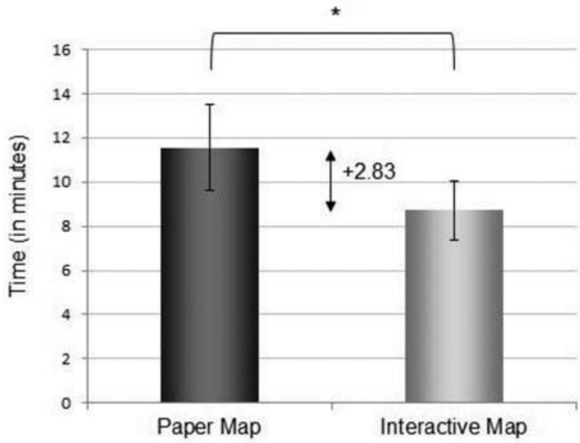
3.1. Short-Term Study: Comparison of the Usability of Different Map Types

The short-term study aimed at comparing the three criteria of usability between the two map types (PM vs. IM). To our knowledge, no prior study has systematically compared the usability of an accessible IM with a classical raised-line map. We made the assumptions that (a) exploration duration (corresponding to the learning time) reflects the efficiency of the maps, (b) the quality of spatial learning (measured as spatial scores) reflects the effectiveness of the maps, and (c) the scores of a SUS questionnaire reflect user satisfaction. In addition, we also evaluated users' confidence in their own responses, assuming a higher confidence when using the IM. An alpha level of .05 was used for statistical significance in every test. Error bars in the diagrams indicate 95% confidence intervals.

Learning Time (Efficiency)

During the experiment, users were asked to learn the map as accurately and as quickly as possible. Learning Time varied from 5 to 24 min with a mean value of 10.1 ($SD = 4.4$). The observed time values were not normally distributed (Shapiro-Wilk

FIGURE 6. Learning Time (mean values measured in minutes) for the paper map (left) as compared to the interactive map (right).



Note. **The Learning Time for the interactive map was significantly lower than for the paper map (lower is better). In other words, efficiency of the interactive map was significantly higher. Error bars show 95% confidence intervals in this and all following figures. *$p < .05$.**

$W = 0.89$, $p < .001$) but logarithms conformed to a normal distribution (Shapiro-Wilk $W = 0.96$, $p = .086$). The logarithm of Learning Time was then compared across map type and order of map presentation in a 2 (map type, within-participants factor) × 2 (order of presentation, between-participants factor) analysis of variance. A significant effect of the map type emerged, $F(1,22) = 4.59$, $p = .04$, as depicted in Figure 6. Learning Time was significantly shorter for the IM than for the PM. We did not observe any effect of the order of presentation, $F(1,22) = 0.24$, $p = .63$, nor significant interactions. Because of the low number of participants we confirmed these results with nonparametric test (Wilcoxon rank sum tests, data not shown). We verified that there was no learning effect between the first and the second map that subjects explored. We also verified that there was no significant effect between the two different map contents.

Spatial Learning (Effectiveness)

To estimate spatial learning we analyzed the scores to the questions on spatial knowledge. We expected that participants would obtain higher spatial knowledge scores with the IM than with the PM.

The sums of the scores (i.e., L, R, and S tasks summed up for each map) varied from eight to 36 and were distributed normally (Shapiro Wilk $W = 0.96$, $p = .089$). They were compared across map type and order of map presentation in a 2 (map type) × 2 (order of presentation) analysis of variance. Although the scores for the IM were slightly higher ($M = 25.6$, $SD = 6.8$) than for the PM ($M = 24.9$, $SD = 6.8$), the effect of map type was not significant, $F(1,22) = 0.45$, $p = .51$). There was no effect of the order of presentation (F(1,22) = 0.08, $p = .79$). We did not observe any significant interaction either (F(1,22) = 1.25, $p = .28$). Because of the low sample number we confirmed these findings with non-parametric tests (Wilcoxon rank sum tests, data not shown). We verified that there was no learning effect between the first and the second map that subjects explored. We also verified that there was no significant effect between the two different map contents. The effectiveness of reading the PM was correlated with the expertise in reading tactile images; as was the effectiveness of reading the IM (see Figure 8). This is not surprising, as both map types are based on exploring a raised-line map overlay.

Differences were observed when looking at average mean scores for L, R, and S questions, both when looking individually at each map (see Figure 7a) and when scores were summed up for the IM and the PM. For summed-up scores, pairwise Wilcoxon rank sum tests with Bonferroni correction (α level = .017) revealed that the difference between L and R was significant ($N = 45$, $Z = 5.20$, $p < .001$) as well as the difference between L and S questions ($N = 43$, $Z = 5.06$, $p < .001$). There was no significant difference between R and S questions ($N = 41$, $Z = 0.41$, $p = .68$).

Finally, Mann-Whitney U Test revealed a significant effect of the order of map presentation on L scores ($U = 149$, n1 = n2 = 24, $p = .004$). L scores were higher if the IM was presented before the PM (see Figure 7b). There was no significant effect of order of presentation for R and S scores. Landmark knowledge for the PM was correlated with the Santa Barbara Sense of Direction Scale (see Figure 8), meaning that people with higher orientation skills obtained better landmark scores. In the same way, landmark knowledge for the IM was correlated with the SBSOD Scale.

FIGURE 7. (a) Mean spatial scores to landmark, route, and survey questions for the paper map (PM) and the interactive map (IM). Mean landmark (L) scores were significantly higher than those for route (R) and survey (S). There was no significant difference between R and S scores. There was no significant difference between the two maps. (b) Effect of order of presentation on landmark scores. The mean scores for L questions were significantly higher when the interactive map was presented before the paper map. $^{**}p < .01$. $^{***}p < .001$.

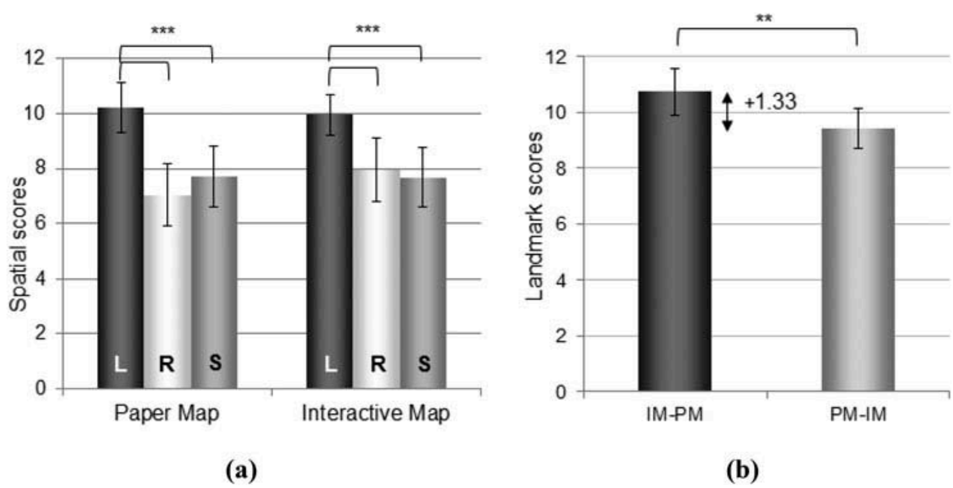
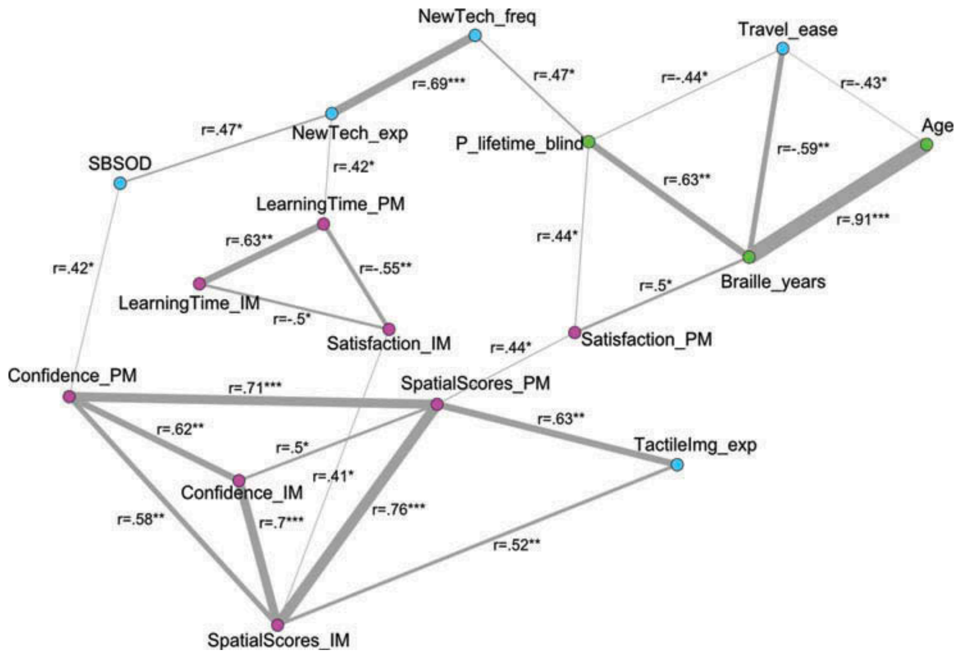


FIGURE 8. Significant correlations between dependent variables (magenta), age-related factors (green) and personal characteristics (blue).



***Note.* The width of the lines between nodes increases with the strength of the correlation (*r* value). exp = expertise; freq = frequency; IM = interactive map; PM = paper map; SBSOD = Santa Barbara Sense of Direction Scale. The diagram was created with the Gephi software (Bastian, Heymann, & Jacomy, 2009). *$p < .05$. **$p < .01$. ***$p < .001$.**

User Satisfaction

We predicted that the IM would yield higher satisfaction, that is, comfort and positive attitudes, than the PM. User satisfaction was assessed with the SUS questionnaire (Brooke, 1996) translated into French (scores between 0 and 100). In our study SUS scores varied between 45 and 100 with a mean value of 83.8 ($SD = 13.9$). Scores were not normally distributed (Shapiro Wilk $W = 0.85$, $p < .001$). They were marginally better for the IM ($M = 86.6$, $SD = 13.7$) than for the PM ($M = 81.0$, $SD = 13.9$), without being statistically significant (Wilcoxon signed-rank test, $N = 22$, $Z = 1.9$, $p = .058$). Yet there was a clear preference among users in favor of the IM: 17 users preferred the IM, six users the PM, and one user had no preference.

The six users who preferred the PM were interviewed about their preference for this map. Two users stated the ease of memorizing written information. One user mentioned interaction problems with the IM, more precisely that there was too much audio output. One user stated that she preferred braille over speech, whereas another one mentioned the ease of use. Finally one user said that the legend of the PM was helpful because it presents a list of all the map elements that the user may find during exploration. We asked the 17 users who preferred the IM which aspect they had most liked or disliked about the map. Seven users preferred speech output over braille text. Four users enjoyed that there was no need to read a legend. Three users enjoyed the ease of use of the IM. One user stated the ease of memorizing spoken text; one user said that the IM was ludic. Finally one user stated the possibility to add supplementary content (like opening hours) on the IM without overloading the tactile drawing. This would not be possible on a raised-line map with braille where the amount of information is limited through the available space.

Further qualitative feedback revealed that many of the participants who preferred the PM, were experienced braille readers and that often these people had spent a longer period of life without sight. This observation was confirmed by a significant linear correlation between the satisfaction of reading PM and the proportion of lifetime without blindness as well as a significant correlation between the satisfaction of reading PM and the braille reading experience (see Figure 8). Of interest, several users with good braille reading skills stated that the IM would be helpful for someone who does not read braille. On the other hand, many of the participants who preferred the IM reported that they were used to interactive devices with audio output, such as the iPhone with VoiceOver. Accordingly, some of them stated that they had problems reading braille. Surprisingly we did not find any correlation between the frequency or experience using new technology and satisfaction using the IM. However, the learning time with the PM was correlated with the expertise in using new technology (see Figure 8); in other words, subjects that consider themselves as new technology experts needed more time for reading the PM with braille text.

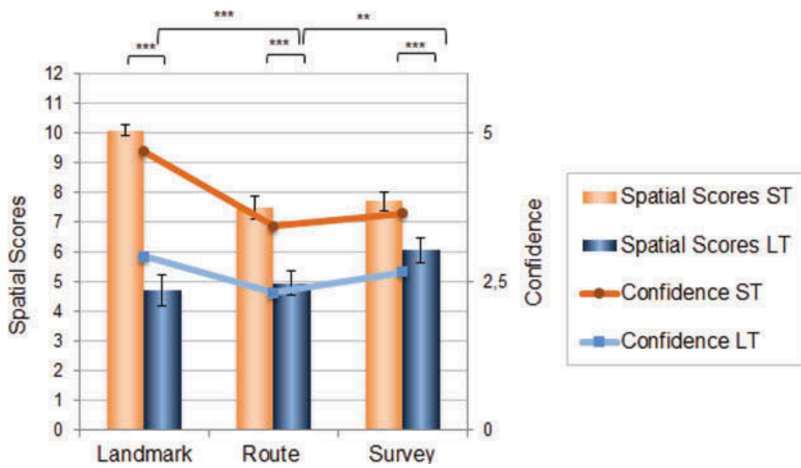
Satisfaction of using one or the other map was correlated with effectiveness (Satisfaction_PM, Satisfaction_IM; see Figure 8). High performers reported a higher satisfaction than low performers. Satisfaction also depended on efficiency: satisfaction was negatively correlated with the learning times for both maps.

Users' Confidence

We expected higher confidence in users' responses when using the IM than when using the PM. Users' confidence in response to spatial questions for the PM varied from 1.83 to 4.67 with a mean value of 3.87 ($SD = 0.68$). For the IM the values varied from 2.5 to 5.00 with a mean of 3.98 ($SD = 0.59$). As scores for users' confidence were not normally distributed (Shapiro Wilk $W = 0.89, p < .001$), we used nonparametric tests. There was no significant effect on users' confidence in their own responses to spatial questions as regards to the map type (Wilcoxon signed rank, $N = 22, Z = 0.84$, $p = .4$) or the order of presentation (Mann-Whitney U Test, $U = 71.5$, n1 = n2 = 12, $p = 1.0$).

However, we observed a significant effect of the type of task (L, R, or S questions) on users' confidence, as shown in Figure 9. Confidence was significantly higher after Bonferroni correction (α level = .017) for L than R (Wilcoxon signed-rank tests, $N = 46, Z = 5.89, p < .001$) or S tasks ($N = 44, Z = 5.75, p < .001$) questions. No significant difference emerged between confidence concerning R and S tasks ($N = 39, Z = 1.56, p = .12$). We did not observe any significant interaction.

FIGURE 9. Mean landmark (L), route (R), and survey scores (bar chart) and self-confidence scores (line chart) observed just after exploration (orange graphs) or 2 weeks later (blue graphs).



***Note.* A significant effect of time is observed: all scores were lower 2 weeks after exploration. The difference was very important for landmark scores but smaller for survey scores. Besides, the figure reveals a strong correlation between confidence and spatial scores (orange) at short term but not at long term (blue). LT = long term; ST = short term. $^{**}p < .01$. $^{***}p < .001$.**

As we expected from visual observation of Figure 9, effectiveness of PM exploration (total score to L, R, and S questions) was correlated with users' confidence in using PM; effectiveness of IM exploration was correlated with users' confidence in using IM (see Figure 8).

3.2. Long-Term Recall: Comparison of the Effectiveness of the Interactive and Paper Maps

The aim of the long-term study was to observe how time affects spatial learning and whether it depended on the map type. To our knowledge no prior study had ever evaluated the long-term memorization of information from accessible IM. This study is important as the aim of geographic maps is to provide a mental representation of space not only immediately after map exploration but also for a longer duration. Visually impaired people specifically reported that they wanted to acquire spatial knowledge that could serve in the future, even if it was not immediately needed (Banovic et al., 2013). Obviously, we made the assumptions that spatial scores and self-confidence would decrease over time. As visually impaired person are used to focus on landmark memorization in mobility perspective, we were expecting a better memorization of landmarks than configurations.

Long-Term Recall of Spatial Information

After a 2-week delay, users were asked exactly the same questions related to spatial knowledge as in the short-term study, without knowing that they would be interviewed on these questions a second time. Hence, we were able to compare scores obtained immediately after exploration and those obtained 2 weeks later. The long-term scores for the PM varied between 4 and 34 with a mean value of 16.54 ($SD = 7.99$). For the IM spatial scores varied between 0 and 35 with a mean value of 14.92 ($SD = 8.78$). These values were not distributed normally (Shapiro-Wilk $W = 0.92, p = .004$). There was no significant effect of the map type (Wilcoxon signed rank test, $N = 24$, $Z = 0.96$, $p = .34$), nor any significant interaction. A main effect of time clearly emerged (Wilcoxon signed rank, $N = 45, Z = 5.84, p < .001$). Short-term scores for both maps varied from 8 to 36 with a mean of 25.75 ($SD = 6.55$). Long-term scores varied from 0 to 35 with a mean of 15.73 ($SD = 8.35$).

Two weeks after map exploration, interesting differences were observed when looking at individual scores for L, R, and S tasks. Pairwise Wilcoxon tests with Bonferroni correction (α level = .017) revealed a significant difference between L and S scores ($N = 40$, $Z = 4.95$, $p < .001$) with the S score being superior (see Figure 9).

It is worth noting that the L score, which was high just after exploration (orange bar), was much lower 2 weeks later (blue bar) with a significant difference (Wilcoxon, $N = 42$, $Z = 5.65$, $p < .001$). Indeed, the decrease from short term ($M = 10.08$, $SD = 2.04$) to long term ($M = 4.71$, $SD = 3.64$) was 45%. A less important but still significant decrease of 21% ($N = 42, Z = 4.72, p < .001$) was observed for R scores. Finally, S scores dropped from 7.69+2.72 to 6.06+3.14, which represents a significant 13% decrease (Wilcoxon, $N = 38, Z = 3.99, p < .001$).

Users' Long-Term Confidence

We asked users about their confidence in responses to delayed spatial questions. For the PM, users' confidence in their own responses varied from 1 to 4.33 with a mean of 2.66 ($SD = 0.99$). For the IM these values varied from 1 to 4.06 with a mean of 2.62 ($SD = 0.99$). Scores for users' confidence were not normally distributed (Shapiro Wilk $W = 0.95, p = .042$). There was no significant effect on users' confidence related to the map type (Wilcoxon signed rank, $N = 23, Z = 0.87, p = .39$). There was no effect of the order of presentation (Mann-Whitney U Test, $U = 267$, n1 = n2 = 24, $p = .67$). A main effect of time clearly emerged (Wilcoxon signed rank test, $N = 48, Z = 5.98, p < .001$) with short-term scores being superior. We observed a significant effect of task (L, R, or S questions) on users' confidence (Figure 9). After Bonferroni correction, confidence was significantly higher for L than R ($N = 42, Z = 3.25, p = .001$), and R than S ($N = 35, Z = 3.01, p = .003$). There was no significant difference between L and S scores ($N = 41, Z = 1.67, p = .09$). In addition, there was a significant effect of time on each score, with short-term scores being significantly higher than long-term scores (Wilcoxon rank sum test, $p < .001$ for the three of them).

4. GENERAL DISCUSSION

The main objective of this study was to compare the usability of an IM and a PM, both designed for visually impaired people. Our hypothesis was a higher usability for the IM, that is, better spatial learning (effectiveness), shorter learning time (efficiency), and higher user satisfaction. This hypothesis was partially confirmed: Learning time was significantly shorter for the IM and more users preferred the IM over the PM. Concerning spatial learning, however, we did not observe any differences depending on the map type, but rather depending on the type of spatial knowledge (L, R, S) and personal characteristics.

We also studied the effect of time on spatial information acquired from the two different map types. This study was important as maps serve the purpose of acquiring spatial information over a long period. We observed interesting significant differences over time regarding the assessed type of spatial knowledge, mainly between L and S scores.

Finally we studied users' confidence in their responses to spatial questions. We observed that users' confidence was closely correlated to their real performance just after map exploration but that 2 weeks later confidence and real performance clearly diverged.

4.1. Comparing Usability of a PM and an IM

Usability of IM for Visually Impaired People

Analysis of the literature revealed that only a few studies systematically and quantitatively compared usability of assistive tools for visually impaired people (see, e.g., Giudice et al., 2012). Therefore, there is little methodology in this area. The present study proposes a protocol for comparing usability of two different map types for visually impaired people. Usability was assessed by measuring (a) efficiency as exploration duration (learning time), (b) effectiveness as the quality of spatial learning (measured as spatial scores), and (c) satisfaction as the scores of an SUS questionnaire and qualitative feedback. This methodology could easily be adapted to different contexts and applications, thus providing an approach for systematic evaluation of assistive tools.

The results show that learning time was significantly shorter for the IM than for the PM–efficiency thus being significantly higher. The longer learning time observed with the PM was certainly caused by the way information is retrieved. For the IM, speech output is obtained immediately during map exploration with a double tap on interactive elements. On the PM many additional actions were required to obtain the same information. First users had to read and memorize the abbreviation, then move at least one hand to the legend, find the abbreviation in the list, read the explanation, and finally move the hand back to the map. This referencing between the map and the legend is time consuming and disrupts the map-reading process (Hinton, 1993).

It might be expected that the decrease in efficiency and the process of referencing both have negative consequences on the effectiveness of the PM compared to the IM. Thus we were expecting better spatial scores (improved effectiveness) for the interactive prototype. Our study did not confirm this finding. We presume that the absence of a measurable effect is related to the small number of elements that were presented on the maps. A greater complexity might have led to different results.

Indeed, the readability and thus the effectiveness of a tactile map is impaired if the map contains a great number of elements and legends (Tatham, 1991). With a richer map that includes more than six items, the greater efficiency of the IM would probably allow better memorization. Then, although this needs to be confirmed with further studies, the IM would probably have a substantial advantage over a classical raised line map with Braille legends.

Finally, we observed a greater satisfaction for the IM with 17 of 24 users stating that they preferred the IM. The three most cited reasons are the use of speech output instead of braille, the fact that there is no legend, and the ease of use for the prototype. Bangor et al. (2008) associated descriptions to scores. They proposed that scores of 100 are "best imaginable," around 85 "excellent," around 73 "good," around 52 "OK," around 38 "poor," and below 25 "worst imaginable." In our study mean SUS scores for both map types were in the range of "excellent" scores. This is not surprising, as both maps were simple maps with few details, and thus rather easy to read. In addition, our users evaluated themselves as experienced in mobility and orientation and expressed their interest in map reading. Except one participant, all had prior experience in reading tactile maps. In our study, we also confirmed another observation by Bangor et al. (2008), which stated that SUS scores are sometimes related to participants' performance (meaning that low performers gave low SUS scores and high performers gave high SUS scores). Indeed, we observed that satisfaction with the PM was correlated with spatial learning scores. The only participant without prior map reading experience scored both maps in the range of marginally acceptable. Most probably, map reading was more difficult for him than for other participants, and he simply did not enjoy exploring maps, independently of the map type. The participant who gave the lowest score for the IM (45) gave a high score for the PM (90). This user (female, age 64) possessed almost 60 years of experience in braille reading. She described herself as a very frequent braille reader with extremely good braille reading skills. She had been visually impaired since birth. We suppose that her above-average braille experience and reading skills as well as the high proportion of lifetime with visual impairment were the reasons why she clearly preferred the tactile PM. This explanation is supported by the fact that, for all users, SUS scores for the PM were positively correlated with braille reading experience as well as the proportion of lifetime with visual impairment. In contrast, SUS scores for the IM were not correlated with braille reading experience or any age-related factor. This means that IM were perceived as accessible even for participants with low braille reading skills. We confirmed this assumption with a blind person not included in the user group of this study (see Brock et al., 2012). This blind person who lost sight when he was 66 years old has limited braille reading skills. A standard raised-line map with braille text was not accessible at all for him, but he could immediately use the IM. He was then able to retrieve spatial information that he could not obtain from a regular PM. A similar result has been observed by Blenkhorn and Evans (1998). Finally we observed that satisfaction with the IM was negatively correlated with learning time for both maps. These different correlations show that the satisfaction is related to the amount of information that users can retrieve from the map they are exploring and the time needed for this task.

The fact that users need less time to retrieve spatial information from a multimodal IM is an important contributing factor for satisfaction.

It may not be surprising that IM provide a more efficient and more satisfying exploration than PM. However, the comparison has never been done before. When looking at studies concerning assistive devices for visually impaired people, we observe that usability has rarely been systematically evaluated, and frequently these studies focus on qualitative results only. When systematic studies are done, the results are not necessarily in favor of the interactive device. For instance, Blenkhorn and Evans (1998) compared an interactive device for exploring schematic diagrams with a hard-copy raised-line diagram. They observed that the interactive system was perceived as more difficult to use and that there was no significant improvement in efficiency with the interactive device. Giudice et al. (2012) conducted a systematic evaluation comparing an interactive vibro-audio prototype with a tactile diagram. Their results showed an advantage for the classical tactile device, although it needs to be stated that their experimental design was different from ours (the interactive device did not include a raised line overlay). They observed that learning time with the interactive prototype was up to 4 times longer than with the paper diagram. In our study, learning time with the IM was significantly shorter. Then the IM was more efficient, and, at the same time, did not rely on additional training. These observations strengthen the importance of systematic evaluation but also underline that the design choice for assistive devices (hardware and interaction techniques) has an impact on usability.

Impact of the Design Choice on the Results

The design space of interactive accessible maps is large and heterogeneous (Brock et al., 2013). We based our design choice on the state of the art of interactive accessible maps in research as well as among commercialized applications. Consequently we designed an IM based on a multitouch device with raised-line overlay and speech output. The design of tactile maps does not obey any standard. First, many production methods exist, and they may have an impact on tactile perception (Picard & Lebaz, 2012). Second, the designer may use an infinite variety of tactile elements—symbols and textures—for representing geographic elements (Edman, 1992). It would have obviously been possible to make different choices. In this study, we did not address if and how these choices impact spatial perception and learning.

As mentioned earlier, the absence of a significant effect in our study is probably related to the low complexity of the maps. Here, we voluntarily focused on low-complexity map to precisely control the map content and lexicon. One particular advantage of IM over PM with braille legend is the possibility to represent a rich and complex environment without making the map cluttered (Hinton, 1993). As an example, it would be difficult to print opening hours of a museum on a raised-line map because braille text takes a lot of space (Tatham, 1991). On an IM this could easily be integrated. It would, for example, be possible to provide several levels of information that are accessible with different interaction techniques (see, e.g., Miele et al., 2006).

In addition, the layers of information could be dynamically updated without modifying the embossed map (Landau & Wells, 2003). Advanced interactions may enable more complicated tasks such as locating specific landmarks (Kane, Morris, et al., 2011), estimating or comparing distances, finding an itinerary, and so on. To go even further, it could be possible to augment maps with users' comments as can be done on some maps for sighted people. Indeed, visually impaired people expressed the wish to share information with peers (Banovic et al., 2013). Although this is just speculation, a more complicated and/or larger map layout would have likely resulted in a greater benefit for the IM condition. Consequently, it would be interesting to design a follow-up experiment comparing paper and IM containing greater spatial information, such as a complex neighborhood or city. One important question would be to identify the quantity of information (e.g., number of items or complexity of the configuration) and/or the complexity of the task corresponding to a significant improvement of effectiveness with the IM.

Some limitations apply to the methodology of this study. The two map types differ in two dimensions: the replacement of braille text by audio output and the absence of a legend. We based this choice on the state of the art of IM, which did not contain braille text or legend. Yet with this design it is not possible to check whether the advantage of the IM with regard to efficiency and satisfaction comes from the absence of the legend or the presence of audio output. To clarify this, a follow-up study should compare three conditions: a PM with braille and legend, an IM with audio and legend, and an IM with audio and without any legend. Qualitative feedback from the participants in our study indicated that a legend can be useful to get an overview over the map content, even when the map is interactive. Consequently we make the prediction that it would be even more usable to include an audio-tactile legend in an IM with tactile overlay.

Of course, the results of this study are limited to the usability of IM, which differ from other devices in that the spatial layout of elements is important (Blenkhorn & Evans, 1998). It would be very interesting to verify whether these results would apply to different types of drawings and diagrams—that is, technical diagrams—for visually impaired people.

4.2. Spatial Cognition in the Blind

Maps are important tools for the acquisition of spatial knowledge. It is interesting to closely look at spatial scores as they can help us understand how visually impaired users acquire spatial knowledge. As previously stated, spatial knowledge is commonly divided in three dimensions: L, R, and S knowledge (Siegel & White, 1975). This theory served as a frame of reference in many studies of spatial cognition. In the present study we assessed the effect of the map type on the learning of the different components (L, R, and S) of spatial knowledge. We looked at this effect immediately after map exploration and with a 2-week delay.

Spatial Memory Following Tactile Map Exploration

Shortly after map exploration, we observed that landmark knowledge was significantly superior to route and survey knowledge and that there was no significant difference between R and S scores. This result is consistent with Magliano et al. (1995) who suggested that the acquisition of route and survey knowledge depended on the previous acquisition of landmark knowledge. This may also be related to the specificity of blind people who preferentially encode the location of selected landmarks (Thinus-Blanc & Gaunet, 1997). Indeed, many of the tools that visually impaired people get to know during locomotion training (e.g., verbal descriptions) are mainly based on the use of landmarks. During direct navigation, these landmarks may be used to mentally select routes and confirm the traveler's position. Landmarks are the initial elements that allow route construction. Of interest, the learning of landmarks in our study was improved if the IM was presented before the PM. We can assume that getting in touch with an IM first might remove apprehension, increase map reading skills, and thus help read any kind of map at a later moment.

The aim of the long-term study was to observe how time would affect spatial memory. Previous studies demonstrated a decrease in precision of spatial information in long-term memory (Giudice, Klatzky, Bennett, & Loomis, 2013). Consequently, we expected that spatial scores in our study would decrease over time. This hypothesis was confirmed as L, R, and S scores decreased 2 weeks after map exploration. The decrease, however, was not uniform for the three types of spatial knowledge. Of interest, L scores were superior to R and S scores immediately after exploration. Two weeks later, this difference not only disappeared but was inverted, with S scores being significantly better than L scores. Looking at details, the decrease was greater for landmark (45%) than for route (21%) or survey knowledge (13%). These results show that survey knowledge is much more robust and does not rely on an accurate and extensive memorization of all landmarks. This observation is particularly important in the domain of spatial cognition and mobility of blind people. It is, indeed, accepted that blind people usually encode spatial information in lower level procedural information, including landmarks and routes and that they do not favor the construction of spatial survey knowledge (see Thinus-Blanc & Gaunet, 1997, for a review). In our study, delayed questions following map exploration show the opposite: Two weeks after exploration, lower level information related to landmark location was forgotten, whereas the high-level information related to configurations was preserved.

Users' Confidence Is Misleading After a Delay of Two Weeks

In the first presentation of an IM, Parkes (1988) raised the question if access to an IM could increase users' confidence in map reading. Until now, this question has not been answered. Following Parkes's proposition, our hypothesis was a higher confidence when using the IM. This hypothesis was neither confirmed at short term nor at long term. Once again, the absence of effect is possibly related to the low complexity content of the map. However, interesting effects emerged. First there was a significant effect of time. Immediately after exploration, there was a strong correlation between users' confidence and effectiveness (spatial scores). Confidence—as with spatial scores—in responses to landmark questions was significantly higher than confidence in route and survey responses. This means that users had a precise self-estimation of their performance immediately after map exploration. Two weeks after exploration, the spatial scores had been inverted with L scores being the least important. Users lost confidence in their own responses but, surprisingly, confidence in L responses remained significantly higher than confidence in R and S responses. After 2 weeks, users' perception of their own performance differed from real scores. A possible interpretation is that blind users are cognitively stuck to what they learned to do, that is, landmark detection, and are thus confident with this task. Yet in reality it appears that IM exploration improves long-term survey knowledge. This is an interesting finding, as survey knowledge is more efficient than landmark and route knowledge to reach autonomous mobility and orientation (Siegel & White, 1975).

4.3. Potential Interest of Interactive Maps

We observed that learning time for the PM was correlated to self-reported expertise in using new technology. In other words, when subjects were confident in using new technologies, they needed more time to explore the PM with braille legend. Many of our blind participants reported that they enjoyed using new technologies (e.g., smartphones) and tended to replace braille books and refreshable braille displays by audio books and audio output. This suggests that an important proportion of blind people do not use braille regularly and less develop braille reading skills. Some of our participants even suggested that, in the long run, audio output will completely replace braille. Nowadays, it is a fact that less than 10% of legally blind people in the United States are braille readers (National Federation of the Blind, 2009). Considering all these reasons, it is obvious that IM are a more viable solution than PM with braille legend.

We also observed that ease of travel was negatively correlated with age and proportion of lifetime with blindness. Older participants and those with a longer duration of visual impairment lose confidence in navigation tasks. This means that they are less used to traveling and consequently risk to get excluded from social life. It is therefore important to propose solutions for this part of the population. Our study also revealed that the proportion of lifetime with blindness was positively correlated with the frequency of using new technology. Then it seems that blind users enjoy new technologies. This opens up a new perspective: Using IM may provide the elderly and early blind with a chance to improve space-related knowledge and to reduce stress and fear related to travel.

5. CONCLUSION AND PERSPECTIVES

Maps present an important means for acquiring mental representations of space. With the rise of new technologies, such as touch screens, many researchers and developers aim to make maps accessible to visually impaired people. In this article we showed that an IM (composed by a multitouch screen, a raised-line map, and audio output) was superior to a tactile PM with braille legend concerning two out of the three dimensions of usability and equivalent for the third one: (a) efficiency, measured as the time needed to learn different types of spatial information, was significantly improved when using an IM; (b) more users expressed a higher satisfaction for the IM—they mostly had a preference for speech over braille output, liked the absence of a legend and the easiness of interaction; and (c) effectiveness, measured as the quantity and the quality of acquired spatial knowledge, was equivalent for both map types. However, we suggest that effectiveness would be improved when using a more complex map including more details (e.g., the map of a neighborhood in a real city). We observed that spatial learning depended on personal skills such as experience with reading tactile images. We also observed that survey-type mental maps were more robust in time than memorization of landmarks and routes. Although this result was not dependent on map type, we think it is of major importance. Indeed survey-type mental maps are more powerful because they can be used to perform various mental manipulations of space (selecting shortcuts, alternative paths, etc.). We conclude that IM may advantageously replace traditional PM for providing visually impaired people with access to spatial and geographic information.

We observed another significant advantage for IM: the improved accessibility for people with low braille reading skills. Contrary to a general thinking, only a small part of the visually impaired population has been trained to read braille. Especially for late blind people, braille represents a great challenge. Through the use of IM, this part of the population could improve mobility and orientation skills and thus gain confidence in traveling. Given the current low prices of tablets and touch screens, schools and associations for visually impaired people begin to adopt this technology for teaching (mainly for providing access to written information). To our knowledge, this technology has not yet been systematically used for teaching spatial content and improving mobility and orientation skills. It would be beneficial to quickly take advantage of this technology, provided that map contents and accessible interaction techniques are designed. For a visually impaired person who owns swell paper, a printer, and a fuser, it would even be possible to create IM at home at a reasonable price. It would just be necessary to provide the community with the digital maps and software.

Finally, it can be argued that IM for visually impaired people are easier to produce if they do not include a tactile map overlay. Indeed, the absence of a tactile map overlay facilitates the creation and dynamic updating of the maps. It also enables new features, such as dynamic zooming and scrolling (Bahram, 2013). However, the presence of tactile cues from an embossed print provides the user with important spatial information (see, e.g., Weir et al., 2012). To facilitate the production of raised-line maps, different projects have proposed the automatic creation of tactile maps, either based on the use of Geographic Information Systems (Miele et al., 2006) or based on image recognition (Wang et al., 2009). In the medium term, we believe that the tactile map overlay will be replaced by deformable surfaces or surfaces with direct tactile feedback (see, e.g., Bau & Poupyrev, 2012; Casiez, Roussel, Vanbelleghem, & Giraud, 2011; Weiss, Wacharamanotham, Voelker, & Borchers, 2011). These interfaces will enable features such as dynamic update, zoom, and scrolling while providing tactile cues. The challenges will then be related to designing advanced interaction techniques that efficiently serve map exploration and spatial learning.

NOTES

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