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Interactive Audio-haptic Map Explorer on a Tactile Display

LIMIN ZENG*, MEI MIAO AND GERHARD WEBER

Human-Computer Interaction, Technische Universität Dresden, Nöthnitzer Straße 46, 01187 Dresden, Germany
**Corresponding author: limin.zeng@tu-dresden.de*

In this article, we propose and evaluate a novel audio-haptic map system to improve map accessibility for the visually impaired while reading city maps and making pre-journey routes. The system employs a touch-sensitive pin-matrix display and represents various map elements through a pre-defined set of tactile map symbols consisting of raised and lowered pins. The interactive user interface allows users to not only acquire auditory and Braille geographic information by touching the involved map elements, but also prepare pre-journey routes by exploring large-scale areas through panning and zooming. Furthermore, the positive results of the evaluation conducted with 10 blind users indicate that blind users are able to use the proposed map system to read street maps and make pre-journey routes in unknown areas, with acquired configurational knowledge and route knowledge. Two-thirds of participants prefer swell-paper maps with only two zoom levels.

RESEARCH HIGHLIGHTS

In this article, we propose and evaluate a novel and interactive map explorer for the visually impaired. The main features of the map application are described as following:

- By employing a touch-enabled pin-matrix display consisting of a matrix of 60 × 120 pins, we can render large-scale tactile city maps.
- To represent various geographic features on city maps, we propose a set of tactile map symbols consisting of raised or lowered pins.
- We develop a number of rich interactive user interfaces for enhancing user experiences while exploring maps, such as panning, zooming and searching. The geographic information can be rendered by audio and Braille representation both.
- Differently to the method to abstract map elements by processing image map data, we describe a method that generates vector-based map data from a geographic information system.
- The map system can be easily extended to render maps for any cities, when the appropriate map data are imported. Moreover, for visually impaired users, it is an automatic method to produce tactile maps.

Furthermore, the proposed system has been compared with swell-paper tactile maps and auditory touch-screen-based maps in terms of reading time and accuracy of preparing pre-journey routes.

Keywords: user studies; haptic devices; accessibility technologies; assistive technologies; people with disabilities

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1. INTRODUCTION

Maps as one of the common daily tools for human beings have evolved with the development of technologies, from ancient maps drawn on animal leather to printable maps on paper and to today's electronic maps rendered on various displays. By exploring a map, users can not only acquire spatial information about selected areas, but can also follow possible route paths to their destinations. However, since most map applications are based on visual representation, for people who have visual impairments it is difficult to access map data, let alone prepare routes correctly and independently.

Tactile maps as a subset of accessible maps are widely accepted by the visually impaired community, due to their touch sensitivity against the fingertips. Since the 1960s, when Gilson *et al.* (1965) pointed out the need for tactile maps, a wide variety of production methods have been proposed, specifically the two dominant methods (Rowell and Ungar, 2003), which are thermoform-based maps (Nolan and Morris, 1971) and microcapsule (or called swell-paper) maps (Andrews, 1985). On the one hand, tactile map readers are able to acquire the spatial layout of geographic features easily via raised lines, symbols and areas represented with special texture, as well as Braille legends. On the other hand, in addition to the time- and labour-consuming production, a series of disadvantages of these traditional tactile maps, such as rendering few static-only map data, limited map size and no interactive features, have failed to fulfil users' increasing demands on exploring maps and preparing routes.

In general, visually impaired people usually make use of assistive tools to access information on computers, like screen-reader software, Text-to-Speech (TTS) output and Braille text. Despite the effectiveness of these tools for rendering text-based information, it is hard to find a good way to represent graphic-based information such as pictures and maps. Although there are a number of assistive electronic wayfinding tools on the market that generate turn-by-turn instructions to destinations, such as various applications on mobile phones and specific mobility aids (e.g. BrailleNote GPS,[1] Trekker PDA[2] and Kapten GPS[3]), these navigation services cannot meet their increasing demands for exploring spatial environments, like acquiring the spatial layout of geographic features in unfamiliar regions. Obviously, an accessible map explorer application is a solution for achieving the goals above. The various map elements on a city map lead to a great challenge to render non-visual map elements on an electronic device, as well as to implement interactive user interfaces.

In this article, we describe our proposal for and implementation of a novel audio-haptic city map explorer, named Hyper-Braille Map (HBMap), in order to improve the accessibility of digital maps for the visually impaired and thereby their independent ability to preparing pre-journey routes. The HBMap is a typical Client/Server (C/S) system, where the server manages map data and the Internet-enabled client employs a touch-sensitive pin-matrix display to render city maps through raised or lowered pins. Aimed at rendering various map elements, the HBMap proposes a set of tactile map symbols, such as streets, bus stops and buildings. Thanks to the touch-sensitive layer on the tactile display, users are able to acquire auditory, tactile and Braille-based geographic information by touching map elements easily. Several interactive features have been developed to support convenient exploration of maps, like panning, zooming and searching.

Furthermore, an evaluation of the HBMap with 10 blind participants was introduced in detail sequentially. To investigate the participants' performances in reading street maps and preparing pre-journey routes on the HBMap, the evaluation compared with their performances while using swell-paper maps and touch-screen based maps. The evaluation shows that most of the participants can use the HBMap to learn about maps and prepare short or long pre-journey routes effectively, via interactive map operations (i.e. panning, zooming). It also revealed that the participants mostly failed to read maps and prepare pre-journey routes on the touch-screen-based maps, due to the lack of tactile feedback while following streets and locating points of interest (POIs). Although there were no significant differences in participants' performances while utilizing the traditional swell-paper maps and the HBMap to read street maps, participants would perform better while preparing long routes with the HBMap system. In addition, two-thirds of the participants preferred swell-paper maps with only two zoom levels.

The remaining sections are organized as follows. Section 2 introduces the background work that surveys different kinds of accessible audio-haptic maps. Section 3 describes the proposed HBMap system in detail, from the system architecture and tactile map symbols to its interactive user interfaces. Then, Section 4 presents an evaluation with blind users. The study ends with a conclusion and suggestions for future work.

2. RELATED WORK ON AUDIO-HAPTIC MAPS

In contrast to traditional non-electronic tactile maps, computer-based audio-haptic maps have become more and more popular over the last decade, from desktop computers to handheld devices. In terms of the various haptic devices employed, the existing audio-haptic maps are classified into four typical categories, i.e. audio-haptic paper-based tactile maps, virtual tactile maps, flat touch-screen-based tactile maps and pin-matrix tactile maps.

2.1. Audio-haptic paper-based tactile maps

Since a common paper-based tactile map contains a number of geographic descriptions in Braille, people lacking Braille reading skills usually require a different approach. For the first time, the *NOMAD* system realizes the audio-haptic approach (Parkes, 1988). The main idea of this approach is that by touching a paper-based tactile map placed on a touch-sensitive pad, the system will speak out audible geographic information

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[1] Trekker PDA, from Humanware, www.humanware.com, last accessed on 7 May 2013.

[2] BrailleNote GPS from SenderoGroup, www.senderogroup.com, last accessed on 7 May 2013.

[3] Kapten GPS, from Kapsys, http://www.kapsys.com/fr/en/products/kapten-mobility/, last accessed on 7 May 2013.

easily. Using such a system normally consists of four basic steps: creating digital maps, producing paper tactile maps, mounting on a touch pad and exploring by fingers.

In the *NOMAD* system, digital maps are drawn manually via computer-aided design software (Parkes, 1994). The *Talking Tactile Tablet* system develops an automatic method to create a street map by processing map data from geographic information system (GIS), but its maps lack various POIs (Miele *et al.*, 2006). Wang *et al.* (2012) implemented another automatic approach to create digital maps by processing image-based maps, which provided a fast way to produce tactile maps. However, at present, when employing image-processing methods, it is a challenging task to recognize the varying categories of POIs (e.g. bus stops and buildings) on maps, and to reach a robust performance in areas with complex and irregular layouts. In addition to a Braille printer for producing paper tactile maps, a touch-sensitive pad was always required in those systems.

Although the method inherits the touch sensitivity of traditional tactile maps and renders detailed auditory information, there are also a number of shortcomings. First, it is still time-consuming to produce paper-based tactile maps, due to the manual or semi-automatic production. Secondly, the map size is limited both by the size of the paper and by the touch pad. Thirdly, the multiple steps while using the map might cause users' difficulties. For instance, while mounting a tactile map on the pad, users have to carefully align the edges of the map and the frames of the pad, otherwise the system may play unmatched information. Most importantly, apart from acquiring audible information by touching, there are no other interactive features, like panning and zooming.

2.2. Virtual tactile maps

The concept of virtual tactile maps was proposed at the beginning of the 2000 (Parente and Bishop, 2003; Schneider and Strothotte, 1999), and their main purpose was to explore maps flexibly through a computer. In contrast to the traditional raised maps, virtual tactile maps have no physical representations of maps, but only have virtual representations on computers. In addition to delivering descriptions via the auditory output, these systems employ a variety of tactile devices (e.g. mouse, joystick, PHANToM force feedback device[4]) to provide spatial information.

Jansson and Pedersen (2005) developed a haptic VTPlayer mouse to access a virtual map. The map prototype in Schmitz and Ertl (2010) informs users when crossing a street with a short vibration like that on a standard rumble gamepad. In particular, to provide better haptic sensation and work in complex environments, the PHANToM devices have been applied in a series of previous systems, such as in Moustakas *et al.* (2007) and Springsguth and Weber (2003). Moustakas *et al.* investigated how blind users utilized a PHANToM mouse to explore a pseudo-3D map (a grooved-line map), and Simonnet *et al.* (2009) demonstrated blind sailors' performance in navigating boats by reading virtual maritime maps, and haptic and auditory street data were rendered by Kaklanis *et al.* (2013).

Compared with paper-based tactile maps which have explicit representation, virtual tactile maps allow interactions with a single point of contact, and hardly enable to support the use of multiple fingers and the palm while exploring maps. Thus, the virtual representation method satisfies only a few visually impaired people who are used to reading maps with both hands in daily life.

2.3. Touch-screen tactile maps

Touch-screen tactile maps present maps on flat-panel touch-screen displays, which allow users to interact by touching the screens. Touch displays were invented in and have developed since the 1960s (Johnson, 1967), and touch gestures have become an interesting human–computer interaction for the blind since the 1980s (Weber, 1987). In the passing years, a number of non-visual representation methods have been investigated to improve the accessibility of touch-screen displays while rendering maps. Auditory representation as an indispensable channel has been adopted in almost all of the related systems. Verbal description and non-verbal-based sonification are the two leading methods for rendering audible information for the visually impaired while exploring maps (Heuten *et al.*, 2006; Su *et al.*, 2010). Furthermore, since the flat touch displays cannot provide explicit tactile sensation against fingertips, the *TouchOver Map* system causes difficulties for individuals with visual impairments in finding out the correct direction of roads, as well as information like whether these roads are closed or not (Poppinga *et al.*, 2011). But the *TouchOver Map* focuses only on rendering streets, without interactions with POIs on maps. On the other hand, a couple of special user interfaces have been developed to improve the accessibility of map explorers on touch displays. For example, *Access Overlays* (Kane *et al.*, 2011) demonstrates how to locate or relocate landmarks on screens, including touching with two hands simultaneously. However, these functionalities seem to be not applicable when exploring a complex city map, which contains a large number of different geographic features.

To enhance spatial tactile feedback, *SpaceSense* (Yatani *et al.*, 2012) employs nine vibration motors attached to the back of a touch-screen phone, to indicate orientation explicitly. Additionally, to provide rich tactile perception of touch displays, a series of novel hardware materials have been invented, not only for the sighted but also for the visually impaired. Among these approaches, the electrostatic touch displays that generate tactile sensations by controlling electrostatic friction between the surfaces and the scanning fingers of users (e.g. *TeslaTouch* display (Bau *et al.*, 2010)) and the tiny film pasting from the

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[4] http://www.sensable.com, last accessed on 8 May 2013.

Senseg[5] corporation have been studied recently for the visually impaired to acquire spatial information. The evaluation by Tang and Beebe (1998), as well as similar results reported in the study of Xu *et al.* (2011), indicates that people who are visually impaired are able to distinguish different simple tactile patterns (e.g. squares and circles) through an electrostatic touch display. However, there is no available map explorer application running on an electrostatic touch display yet. Owing to the weak tactile sensation of electrostatic touch surfaces, it may be challenging to represent various geographic map objects by designing distinguishable tactile icons.

2.4. Pin-matrix tactile maps

In contrast to electrostatic touch displays, the emerging pin-matrix tactile displays provide better tactile sensation through raised or lowered pins. Vidal-Verdú and Hafez (2007) surveyed previous studies on designing pin-matrix displays. In terms of the different kinds of substrates, generally there are two leading categories. The first one makes use of varying electromechanical actuators, such as piezoelectric refreshable actuators (Linvill and Bliss, 1966; Pasquero and Hayward, 2003; Völkel *et al.*, 2008), voice-coil motors (Shinohara *et al.*, 1998; Szabo and Enikov, 2012) and shape memory alloys (Velázquez *et al.*, 2006). The second type is based on various chemical polymer materials that can be bent or expanded, such as in Kwon *et al.* (2009) and Wu (2008). Since there are advantages to pin-matrix displays for rendering graphical information, a number of research projects have been conducted to develop large-scale pin-matrix displays, such as the European *ITACTI* display[6] (a matrix of 128 × 64 dots), the *Anagraphs* display[7] (6000 Braille dots) and the German HyperBraille display[8] (a matrix of 60 × 120 Braille pins). While benefitting from the mature manufacturing technologies of piezoelectric Braille displays, piezoelectric pin-matrix displays are becoming commercially available at present, like the HyperBraille display and KGS's DOTVIEW 2.[9]

Pin-matrix displays equipped with a small amount of pins, like the haptic VTPlayer mouse with two matrices of 4 × 4 pins, are difficult to utilize for rendering a large-scale street map. Shimada *et al.* (2010) illustrated an overview European map on a pin-arrayed display with a matrix of 32 × 96 pins; however, the maps were generated by image proceedings that did not allow presentation of complex tactile objects nor further interaction with them, like zooming and panning. Moreover, Shimada *et al.* did not render a city map and evaluate how blind users acquire configurational knowledge by reading tactile maps. Despite the development of several large-scale pin-matrix displays (e.g. the HyperBraille display), there is no appropriate tactile city map system.

2.5. Tactile map symbols

Due to the different kinds of substrates (e.g. microcapsule paper, thermoplastic, embossing paper, etc.) employed to produce tactile maps, a number of different sets of tactile map symbols have been designed and developed. The symbols of the Nottingham Map Making Kit (James and Amstrong, 1975) and the Euro-Town-Kit (Laufenberg, 1988) have been popular for making traditional thermoplastic or microcapsule paper-based maps. McCallum *et al.* (2006) evaluated a different set of directional symbols on tactile maps made by an ultraviolet curing polymer inkjet process. Although Miele *et al.* in the TMAP system developed single-line street symbols for embossing printers, the tactile symbol set did not contain POI symbols (Miele *et al.*, 2006). Furthermore, a few previous studies focus on designing tactile map symbols for pin-matrix displays.

As shown in Table 1, the existing tactile maps on pin-matrix displays not only have a small map size, but also lack rich interactive features.

3. AN INTERACTIVE AUDIO-HAPTIC MAP EXPLORER ON A PIN-MATRIX DISPLAY

In this section, we introduce an interactive audio-haptic map explorer for people who are visually impaired, named HBMap. In addition to a novel tactile representation of city maps on a pin-matrix display, a series of rich interactive map operations have been proposed, such as panning, zooming and searching.

3.1. The applied pin-matrix display

The map explorer adopts a HyperBraille display (Völkel *et al.*, 2008), consisting of a matrix of 60 × 120 equidistant pins, called the work area. Several physical keys are arranged around the work area. A capacitive sensor layer has been integrated into the work area, and enables touch input. Each pin is driven by a piezoelectric actuator, and is either lowered or raised by 0.7 mm. The complete screen can be refreshed promptly (in about 150 ms). The display connects to a host computer via a standard USB cable.

3.2. System architecture

The HBMap system has a typical Client/Server (C/S) structure (see Fig. 1). A server supports storage and management of map data, as well as a number of Web service interfaces for communicating with clients. Since a mainstream GIS server has been adopted, the system manages worldwide map data

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[5] Senseg Company, http://senseg.com/experience/senseg-experience, last accessed on 15 May 2013.

[6] ITACTI project, http://www.smarttec.co.uk/itacti/home.htm, last accessed on 18 May 2013.

[7] Anagraphs project, http://www.anagraphs.eu/, last accessed on 18 May 2013.

[8] HyperBraille project, http://hyperbraille.de, last accessed on 18 May 2013.

[9] KGS Company, http://www.kgs-jpn.co.jp/, last accessed on 18 May 2013.

Table 1. Comparison of available computer-based tactile maps.

	Audio-haptic paper-based tactile maps	Virtual tactile maps	Touch-screen tactile maps	Pin-matrix tactile maps
Map size	Medium (limited both by the paper and touch pad)	Large	Medium (limited by the display)	Small (32 × 96 pins)
Amount of maps data	A few	A large number	A large number	A few
Map elements rendered	Tactile map symbols	Tactons	Earcons	Tactile symbols
Provision of spatial layout	Yes	No	Yes	Yes
Map production	Semi-automatic	Automatic	Automatic	Automatic (by image processing)
Reading manner	Touch with fingertips (both hands)	Control devices with a hand	Touch with fingertips (both hands)	Touch with fingertips (both hands)
Interactive features	Tapping; No panning; No zooming	Clicking; Panning; Zooming	Tapping; Panning; Zooming	Tapping; Panning

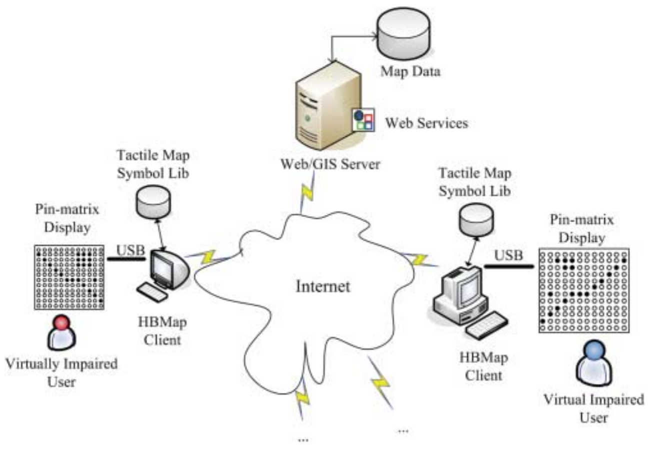

Figure 1. The system architecture of the HBMap.

easily. The current HBMap system imports map data from the OpenStreetMap[10] (OSM), a free and crowd-sourcing map data provider. On the client side, apart from a pin-matrix display connected to an Internet-enabled computer, specific client software developed by us is required to represent and interact with maps.

In general, most map applications (e.g. Google Map) on computers or mobile devices render maps based on a set of visual raster tiles, which are generally inaccessible to the visually impaired. The HBMap Client renders geographic features by processing vector-based map data that contain detailed attributes of map objects, as well as geographic layout information.

As one kind of vector-based map data, Geography Markup Language (GML) has become an ISO standard (ISO 19136:2007[11]) for the transport and storage of geographic information. Due to the detailed descriptions and precise location information enveloped in GML format messages, map elements can be rendered on different mediums, not only on regular visual monitors, but also on tactile displays. The GML map data are required and transported via the Web Feature Service (WFS), an Open Geospatial Consortium standard. In the HBMap, the open-source GIS software server GeoServer[12] is adopted to transport geographic features from the server to the clients.

3.3. Non-visual representation by tactile map symbols

When representing digital city maps on visual monitors for the sighted, a wide variety of map elements are rendered in different styles (e.g. icons, colours and lines), and some of them can even be overlapped. Rendering a city map on a pin-matrix display addresses several design issues. The first one is how to present a number of different kinds of map elements through raised or lowered pins. Secondly, its resolution (even with 7200 pins) is still not adequate to render a large-scale area as detailed as possible. Thirdly, the large space between each pin (ca. 2.5 mm) will impact on the detailed shape of map objects, specifically for rendering oblique lines. More importantly, it is not suitable to overlap more than two static map elements on the pin-matrix display, otherwise users might be confused while touching the incomplete tactile objects.

In order to represent a city map on a pin-matrix display, therefore, a comprehensive and applicative strategy should be adopted. The HBMap system renders map elements via various tactile symbols consisting of lowered and raised pins. Fourteen kinds of map symbols are designed, and refer to everyday

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[10] OpenStreetMap, http://www.openstreetmap.org/, last accessed on 25 May 2013.

[11] ISO 19136:2007, http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=32554.

[12] GeoServer, http://www.geoserver.org/, last accessed on 28 May 2013.

categories of map elements for the visually impaired. Figure 2 illustrates some of the HBMap tactile map symbols. While designing these tactile map symbols, we relied on some of the existing symbols in previous studies that can be rendered on a pin-matrix display, like the single-line street symbol employed in the Nottingham Kit and the TMAP system. It is important to ensure there is enough space between symbols, to make each symbol distinguishable.

With the help of the pre-designed tactile map symbols and the GML-based geographic map data, the HBMap system renders a non-visual representation of various map elements through the raised or lowered pins, as demonstrated in Fig. 3.

3.4. Data flow for supporting interactive functionalities

From the perspective of system data flow, the HBMap system consists of seven main steps to represent maps on a pin-matrix display and respond to users' interactive explorations, as addressed in Fig. 4. The tasks of the seven steps are listed as follows:

- Step 1: Users make map exploration interactions on the display, e.g. panning and zooming, and the Interaction Module receives involved commands;
- Step 2: In line with the commands from Step 1, a WFS request is generated by the Interaction Module, and then sent to the remote server;
- Step 3: After extracting the vector map data from the GIS server, the responding map data in GML format are generated and sent to the clients;
- Step 4: When the GML map are received by the clients, a GML Parser Module is used to classify and process the raw GML data;
- Step 5: A feature filter simplifies the raw GML data by filtering untargeted geographic features;
- Step 6: The corresponding tactile map symbols of map elements are retrieved from the built-in symbol library;
- Step 7: The Presentation Module renders the map symbols one by one on the pin-matrix display.

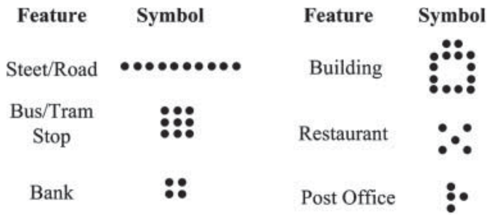

Figure 2. Parts of pre-designed tactile map symbols (black dots mean raised pins).

3.5. Interactive user interface

In particular, the Interaction Module of the HBMap system implements map operations (e.g. panning and zooming) that allow users to explore city maps in the following ways:

(1) *Acquiring auditory geographic information*: thanks to the touch-sensitive sensors placed on the top of the tactile display, the HBMap system is able to play relevant auditory information of the map symbols touched by a fingertip (e.g. name and category). To reduce the impact of system responding time (e.g. commands calculated on the server), users always need to press a physical button to acquire geographic information, rather than instantly speaking out while touching map elements.

(2) *Acquiring Braille geographic information*: most Braille readers prefer reading information in Braille. In order to output Braille geographic descriptions, a specific Braille window is placed at the bottom of the display. Figure 4 demonstrates how the Braille window renders information about a tram stop in Braille, such as name, line number etc. As an optional function, users can easily switch it on or off. Furthermore, it makes the HBMap system accessible for deaf-blind persons who have Braille skills.

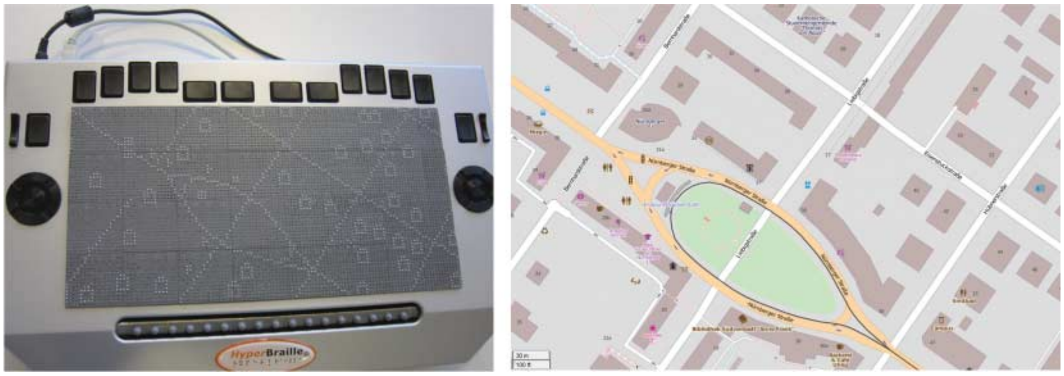

Figure 3. A part of Dresden City map presented by the HBMap system (left: non-visual representation on a HyperBraille display; right: a screenshot of the vision-based map from the OSM site). (The map rendered is around the area of 'Nürnberger Street' in the city of Dresden.)

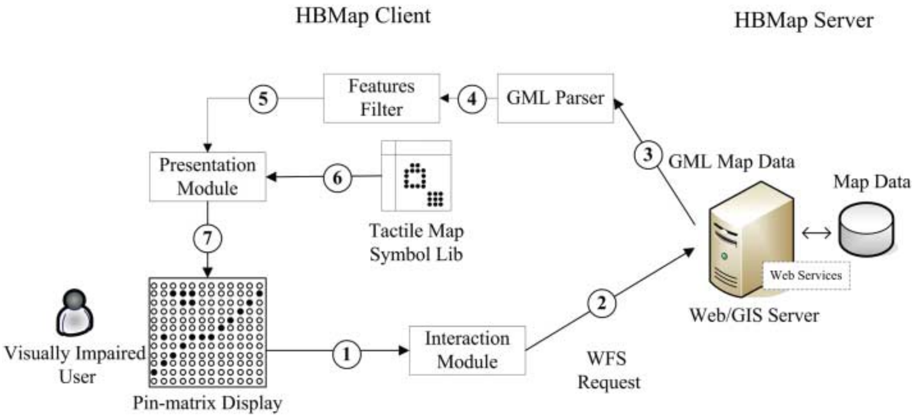

Figure 4. The data flow for supporting interactive map explorations.

(3) *Panning maps by gestures*: as demonstrated in Schmidt and Weber (2009), who developed several multi-touch gestures on the HyperBraille display, the HBMap implements panning gestures as well. While panning, the map will be refreshed according to the movement of the finger in contact, including the moving direction and distance. Note that irrespective of before or after panning, the focus symbol or area is always touched by the finger. Thereby, visually impaired users would quickly explore the new areas without the needs to spend extra time on relocating the previous focus.

(4) *Zooming maps*: aimed at representing city maps both in a large-scale area and in detail, a map zooming strategy has been developed for the HBMap system. According to the zoom level (i.e. map scale), different geographic features will be rendered on the map in different views. For example, a *Street View* (with a low value of map scale) renders only the street network, but covers a large-scale area. When zoomed into a *POI* view, not only the streets but also various POIs are presented, and the map area rendered becomes smaller. The detailed shape of a building can be represented while zooming in further. The zoom levels are continuous. In particular, the size of the tactile map symbols is not changed after both zooming in and zooming out.

(5) *Searching POIs*: this function allows users to locate targeted POIs easily and quickly, particularly for unknown POIs. Hence, the HBMap system provides the POI search function by inputting the targeted POI name from a keyboard. To reduce the locating time sharply, the POI selected from the search result list will be rendered in the centre of the display and blink[13] until users' next operation.

In summary, the proposed HBMap system has several strong points that have not been included in previous studies. First, it employs a larger touch-enabled pin-matrix display (60 × 120 pins) than the one currently available (Shimada *et al.*, 2010). It uses vector-based map data to reduce overhead. A city map consisting of a set of pre-designed tactile map symbols can be explored through the haptic sensation, and the HBMap system allows visually impaired people to explore arbitrarily large maps through interactive operations such as panning, zooming and even searching.

4. SYSTEM EVALUATION

The previous evaluation with blind participants (Zeng and Weber, 2010) indicated that users were able to access geographic data through the proposed system. However, it is still not clear about participants' performance while preparing pre-journey routes with the help of the HBMap system, particularly in unknown regions. As a novel and emerging map application, it is also unclear how the users' performance in planning routes on the HBMap system differs on the traditional tactile maps and the maps on regular touch-screen displays. To further investigate the questions above, an evaluation is introduced in this section.

In addition to the proposed HBMap system on a pin-matrix display, therefore, the evaluation includes two other mediums for rendering accessible maps, which are swell papers and Apple's iPad tablet,[14] respectively. The evaluation focuses on three basic map operations: acquiring geographic information, panning and zooming while exploring maps. The geographic information concerns configurational knowledge and route knowledge (Kitchin and Jacobson, 1997). Therefore, apart from the HBMap system, the other two maps have to implement panning-enabled and zoom-enabled functions. To simplify the complexity of the evaluation, each map would only be allowed

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[13] The blink animation lowers and raises pins alternately in a low frequency (about 1 Hz).

[14] A 10-inch flat touch-enabled pad, http://www.apple.com/ipad/overview/, last accessed on 6 June 2013.

to zoom in/out at two levels. The first zoom level with a low map scale renders streets only, namely ‘*Street View*’, while the second zoom level with a larger map scale presents both streets and POIs, called ‘*POI View*’.

Moreover, the evaluation collects a series of aspects to assess users’ performance quantitatively and qualitatively, from spending time on exploring maps to subjective user feedback. In particular, to measure how much spatial information was learnt by participants, we applied a multiple-criteria method to evaluate the participants’ mental maps, with respect to configurational knowledge and route knowledge on the three different test mediums.

4.1. Participants

Ten individuals with blindness (four females and six males, M = 31.6 years, age range: 20–50 years) took part in the evaluation. They had different job occupations, from college student, translator, teacher and program tester to telephonist. All the subjects had some Braille skills, and six of them were good at it. Most of them used tactile maps in daily life, although three subjects utilized them rarely, and all of them reported that they usually used a tactile map for pre-journey purposes. In addition, the subjects had good experience of swell-paper maps, but limited experience of touch-screen devices and the HyperBraille display. Only Participant 1 (P1) and P3 used touch-screen devices every day, and P7 had had few personal experiences with maps, touch-screen devices and the HyperBraille display. Additionally, some participants already used the HyperBraille display for reading Braille (Prescher *et al.*, 2010).

4.2. Materials

As the participants needed to evaluate all of the three different mediums, three maps were prepared in advance. To make the three test maps unfamiliar to all the participants, we selected three areas in other cities, located in Germany. Note that before the evaluation, each subject confirmed that they did not know any of the test areas. The three maps represented nearly an equal number of streets and POIs, as well as equal coverage[15] (see Fig. 5). All selected POIs are common resident buildings. These maps are typical European city maps with irregular structures that are different to regular street blocks in the USA. In addition, we defined the starting POI, and the ending POIs for a short route and a long route, respectively, on each test map.

4.2.1. *The test maps on swell paper*

We manually produced the three test maps on swell paper, according to the guidelines recommended by the National Mapping Council of Australia (NMCA, 1985). The maps were produced on A4-size swell papers (see Fig. 6). In order to produce panning-enabled and zooming-enabled swell-paper-based maps, each *POI View* map is separated into four sub-maps, as illustrated in Fig. 7, and the four sub-maps are banded in order while evaluating. Therefore, users have to turn to different sub-maps to simulate the processes of panning and zooming.

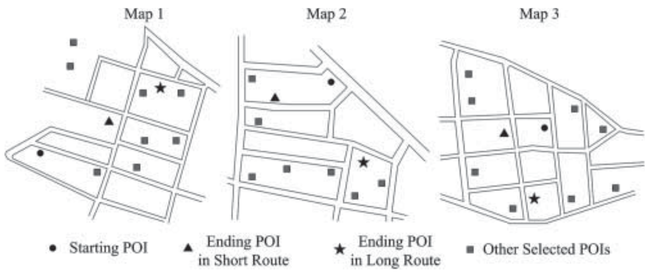

Figure 5. The layout of the three test maps and locations of starting and ending POIs.

4.2.2. *The test maps on a touch pad*

Since the current map explorer applications on flat touch-screen displays include too many unnecessary map elements that will impact on the evaluation, we developed a Scalable Vector Graphics (SVG)-based prototype map system to render the three test maps on an iPad device. Like most of the touch-screen applications, the prototype mainly outputs auditory information to inform street/POI names, while being touched. In the *Street View* (see Fig. 8 (left)), only some selected streets are open for interaction. In addition to the street names, the prototype says the cross-street names at the intersection sites as well. In the *POI View*, the map is rendered in the centre of the display, and four panning buttons are placed around the map area (see Fig. 8 (right)). When pressing the panning button concerned, the map will translate a fixed distance (e.g. half of the height/width of the map area). Two zoom buttons are placed at related pages to switch between street view maps and POI view maps. The prototype only renders the areas within the three test maps, thus, a line is added at each border of the test maps. While touching the border line, a non-verbal sound will be played to alert the users. Furthermore, as the prototype is a stand-alone application without a remote server, it can quickly respond to users’ interactions, like saying the names of streets or POIs.

4.2.3. *The test maps on a pin-matrix display*

The POI search function of the HBMap system requires participants’ computer skills to input names of POIs from keyboards and use screen-reader software. To focus on comparing the performance of exploring maps via panning and zooming, the searching POIs function is not to be evaluated in this study. Several physical buttons are adopted to trigger map operations. The tailored panning function only allows maps to be translated in four directions (i.e. left, right, up and down), which requires one hand to press a physical panning button and one hand to do the correct finger-panning gestures. Two physical

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[15] The three test maps only render the main streets and selected POIs in the areas.

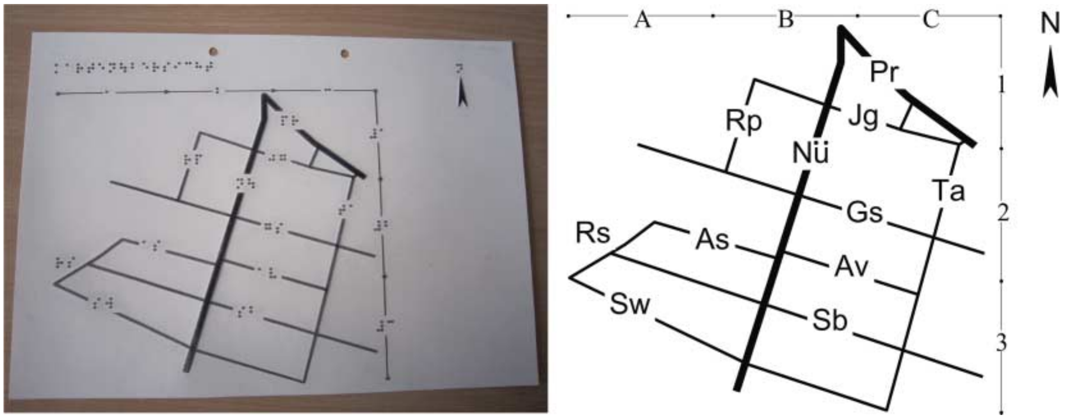

Figure 6. The street view of Map 1 on swell paper (left: the version with Braille text for visually impaired subjects; right: a transformed version for the sighted).

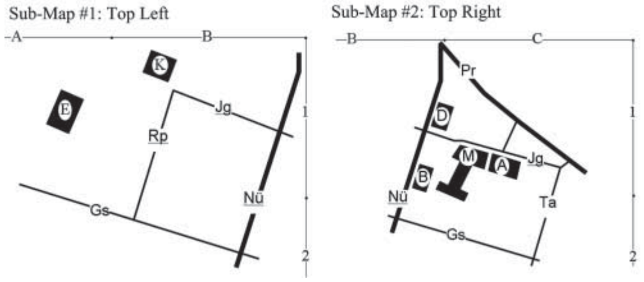

Figure 7. Examples of two sub-maps of Test Map 1 in ‘POI View’ (a visualized version for sighted readers).

buttons are used for zooming in and out, as well as a button for enabling speech out. Figure 9 provides an overview of the usage of the physical buttons in *Street View* and *POI View*.

4.3. Procedures

A series of systematical processes are conducted in order, consisting of training for each platform, an exploring street view maps test, a preparing pre-journey plans test and a post-questionnaire to acquire subjects’ feedback. With regard to the aspect of ethics, the study was conducted according to the Ethical Guidelines for Educational Research (British Educational Research Association, 2011). Before the evaluation, the subjects were informed clearly about the steps of the experiment and their roles. The evaluation started when the subjects agreed to participate. Meanwhile, they were informed that they could quit or cancel any tasks if they felt too difficult for them. There was no time limitation for accomplishing each test. We were permitted to record the participants’ performance through a video camera, and the video files were used for analysing results.

(1) *Training*: Before the formal evaluation of each platform, all of the participants had to learn skills in the training period for all of the three mediums, such as how to get street/POI names and how to apply panning and zooming in/out. Additionally, once the subjects had completed the training tests, the main experiments would start.

(2) *Exploring Street View Maps Test*: The task of the test (Task 1) was to let the participants explore the three street view maps on the three platforms firstly, and then ask them to rebuild the street maps with magnetic strips on a metal whiteboard. While rebuilding the mental maps of streets, they needed to try their best to remember and identify the street names. At the end of Task 1, two five-point scale questions were prepared for them (1 = strongly negative, 5 = strongly positive).

Q1: How easy do you think it was to follow streets with your fingers?

Q2: How easy do you think it was to get names of streets?

In this study, to measure accuracy of participants’ mental maps of streets built, a comprehensive multi-criteria measurement was employed by considering multiple practical features (Miao and Weber, 2013). With respect to configurational knowledge, in the adopted method nine metrics including their corresponding weight values are proposed to measure the distance (D) between the original map features x_i and the built mental map features y_i (see Table 2). Note that their weight values w_i were defined with the help of 21 blind people (see Miao and Weber, 2013).

The distance (error) between the original map and the mental map is calculated based on the nine metrics as follows:

$$d(x, y) = \sum_{i=1}^{9} w_i \times |x_i - y_i|$$

(3) *Preparing pre-journey plan test*: In this task, there were two sub-tasks that the participants needed to complete while reading the *POI view* maps. The first one (Task 2) was to plan a short route between two nearby POIs, while the other one (Task 3)

was to plan a long route between two distant POIs. In the short route, since the two close POIs could be rendered on the same screen/paper, participants did not need to pan the maps to reach each other in Task 2. However, in the long route, users had to pan the map from one targeted POI to another one. The subjects needed to build their planned routes with magnetic strips for streets and small magnetic plates standing for starting/ending POIs.

When the subjects had finished building long/short routes, they were asked six five-scale point questions (1 = strongly negative, 5 = strongly positive). Q3–Q5 were targeted at building a short route, while Q6–Q8 addressed for building a long route.

Q3: How easy do you think it was to locate the two POIs?
Q4: How easy do you think it was to get names of POIs?
Q5: How easy do you think it was to find out the short route?
Q6: How easy do you think it was to locate the two POIs?
Q7: How easy do you think it was to get names of POIs?
Q8: How easy do you think it was to find out the long route?

We prepared a number of magnetic strips that had five different lengths, and the participants could use any one of them to build mental maps of streets and routes that they had learnt. Meanwhile, several small magnetic plates were prepared to stand for the starting/ending POIs. Before the main tests, the participants had already been informed that, while building street maps or routes, they were not allowed to read the original maps again. In order to avoid the order effect, the arrangement was carefully prepared in advance, and the uses of the three test maps and the three mediums were counterbalanced.

For evaluating the mental maps with respect to route knowledge, we used the method by Miao and Weber (2013), as differed to the seven error metrics applied in the *SpaceSense* project. The distance (D) between the reconstructed route and the original route is measured from two aspects: the distance of the structure of street segments (D_S) and the distance of the properties (i.e., street name, street shape and street direction) of street segments (D_M). D_S consists of three metrics:

- d_1: referring to the first turn (right or left) from the starting POI to the first street segment (weight = 0.37)
- d_2: referring to the number and order of the street segments (weight = 0.37)

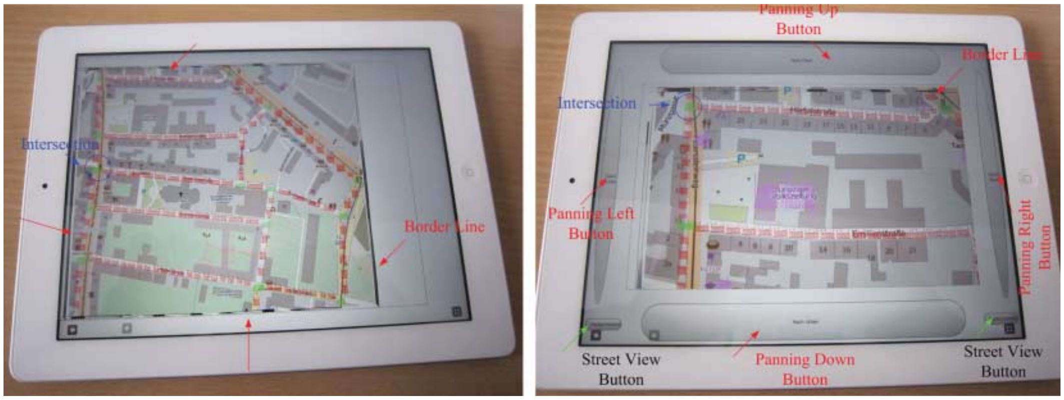

Figure 8. The screenshots of Map2 on iPad.

Figure 9. Screenshots of Map 3 on the HBMap system (left: the *Street View*; right: the *POI View*).

Table 2. Criteria and their weights for evaluating distance between original and mental maps.

No.	Criterion	Weight	Original map	Mental map
C1	Number of correct street segments	0.31	x_1	y_1
C2	Number of correct remembered street names	0.28	x_2	y_2
C3	Number of correct street shapes	0.28	x_3	y_3
C4	Number of correct assigned street names	0.28	x_4	y_4
C5	Number of correct street directions	0.13	x_5	y_5
C6	Number of correct crosses and branches	0.31	x_6	y_6
C7	Number of non-existent streets	0.31	0	y_7
C8	Number of non-existent crosses and branches	0.31	0	y_8
C9	Number of displacements of streets	0.31	0	y_9

- d_3: referring to the last turn (right or left) from the last street segment to the ending POI (weight = 0.37)

D_M consists of three metrics as well:

- d_4: referring to the number of correctly assigned street names (weight = 0.26)
- d_5: referring to the number of correct street shapes (weight = 0.26)
- d_6: referring to the number of correct street directions (weight = 0.11)

Therefore, the distance (error) D is calculated as follows:

$$D = \sum_{i=1}^{6} W_{d_i} \times d_i$$

(4) *Post-questionnaire*: a number of questions were prepared at the end of the evaluation, which refer to their ranks for the three platforms, and the pros and cons of the iPad-based maps and the HBMap system.

4.4. Results

M1, M2 and M3 stand for the swell-paper map platform, the iPad platform and the HBMap system accordingly.

4.4.1. *General results*

Since the subjects had different capabilities and experiences, some of them gave up on several tasks that were difficult for them, although all of them passed the related training tests. Most of the subjects who were able to finish the tasks on the swell-paper maps and the HBMap system, however, failed to prepare pre-journey routes on the iPad map system. Table 3 reveals their completion on the three platforms. All the subjects built street maps on the swell-paper maps and the HBMap system. But four subjects were unable to reconstruct the street view maps while reading maps on the iPad platform, despite having tried patiently for a long time. Nine of the 10 subjects built long routes by using the HBMap, which was more than those using swell-paper maps (eight subjects) and the iPad map (three subjects). Only five built short routes on the iPad platform. Moreover, P7 gave up on all of the tasks for building short/long routes, which might be because she had little map use experience. Note that the data of the subjects who did not complete the related tasks have been left out in the following result analysis.

Table 3. Completed tasks per platform.

No.	Task	Swell-paper map	iPad map	HBMap
1	Building a street map	10	6	10
2	Building a short route	9	5	9
3	Building a long route	8	3	9

4.4.2. *Results on map-reading time*

We documented their time spent on reading maps, which did not include the time spent on reconstructing mental maps with magnetic materials. Figure 10 shows the overview reports on their mean map-reading time for the three tasks. For reading both street view maps and POI view maps, we did not find any significant difference among the three platforms by using the dependent t-test statistics analysis pair by pair, respectively.

The participants spent more or less equal time while reading maps on the swell-paper maps (Task 1: M = 5.36 min, SD = 3.06; Task 2: M = 3.51 min, SD = 2.2; Task 3: M = 4.17 min, SD = 2.15) and the HBMap system (Task 1: M = 4.27 minutes, SD = 1.33; Task 2: M = 3.98 min, SD = 2.98; Task 3: M = 4.12 min, SD = 4.94). However, they spent considerably more time on the iPad platform for Task 1 (M = 10.06 min, SD = 7.0) and Task 2 (M = 9.46 min, SD = 5.25), than on the other two platforms. On the other hand, the three subjects who accomplished the task to build long routes on the iPad spent less reading time for Task3 (M = 2.47 min, SD = 2.27); perhaps, they had become more familiar with the test maps after the previous tasks for Tasks 1 and 2.

4.4.3. *Results of mental maps with respect to configurational knowledge*

Although some of the participants reconstructed mental maps with respect to configurational knowledge after exploring maps

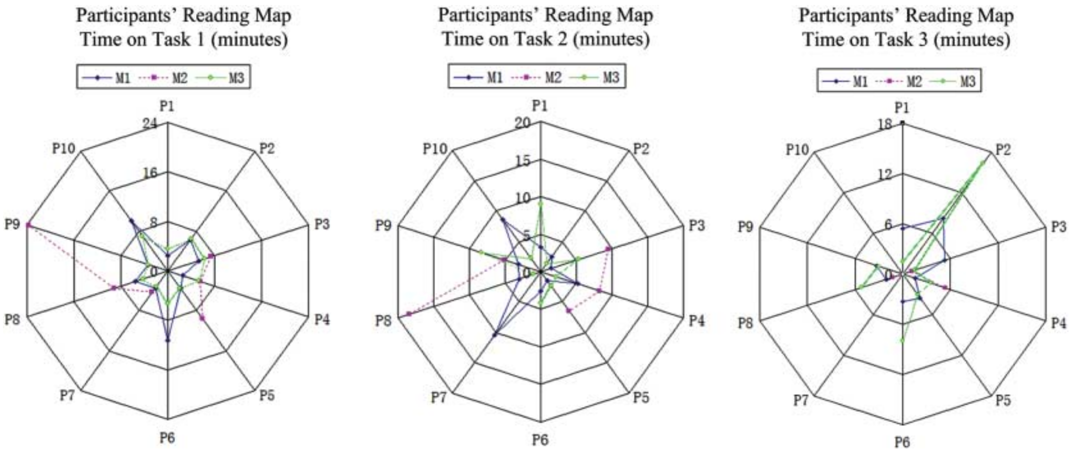

Figure 10. Participants' map-reading time for the 3 tasks.

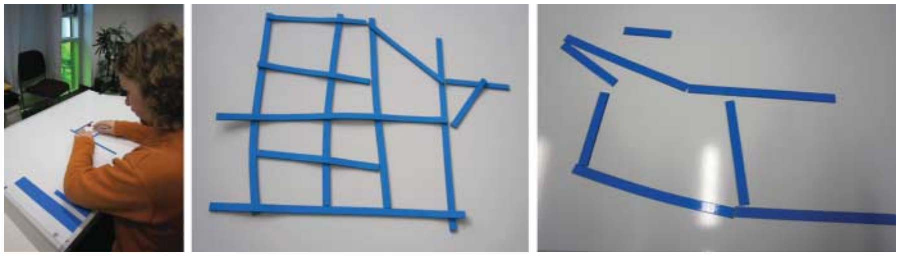

Figure 11. Examples of mental maps reconstructed with magnetic strips for Map 3 (left: a participant building maps with magnetic strips; mid: a composition close to the correct layout by P1; right: an incorrect composition by P7).

on different platforms, they had varying performances, as shown in Fig. 11.

Since we evaluated the three different maps that have various streets and POIs, in order to normalize the results, the error rate of each criterion is calculated one by one at first. According to the results of the paired t-tests (at the 95% confidence level) depending on the participants rather than the test maps or the platforms, there was no significant difference between the swell-paper platform and the HBMap system. Moreover, M1 and M2 had significant differences in C1 and C6, and M2 and M3 had significant differences in C1 and C8, respectively.

4.4.4. *Results of mental maps with respect to route knowledge*

The participants had different performances in rebuilding the pre-journey routes as well, either building the short routes (see Fig. 12) or building the more difficult long routes (see Fig. 13).

4.4.5. *Accuracy of building short routes*

When building the short pre-journey routes, nine subjects finished Task 2 on M1 and M3, but only five subjects completed on M2. Table 5 indicates the nine subjects' mean error rate while building the short routes on M1 and M3, and there was no significant difference found by paired t-test between M1 and M3 (t = 1.3, df = 7). In particular, the participants had better performances by reading swell-paper maps than the HBMap system on the criterion of d5 and d6. Moreover, the mean error by the five subjects who finished Task 2 on the iPad map system to build the short routes by reading maps is 4.3% on M1 and is 18.0% on M2, respectively, where there is no a significant effect (t = 1.04, df = 4).

4.4.6. *Accuracy of building long routes*

The eight subjects' accuracy of building the long routes while using swell-paper maps and the HBMap system reached 20.7 and 20.5%, accordingly, and the paired t-test did not find a significant difference on the six metrics (t = 0.02, df = 7). Meanwhile, the three participants who completed the task on the iPad platform had a higher mean error rate (21.7%) than they performed on the HBMap (8.7%).

4.4.7. *Results on subjective feedback on the three platforms*

After each sub-task the subjects had to give their feedback on the three platforms while reading maps. They reported that it was hard to follow streets (Q1: M = 2.75) and locate starting/ending POIs (Q3: M = 2.0 and Q6: M = 1.8) on the iPad platform, but they would do better both on the swell-paper maps and on the HBMap system. In contrast, they were more satisfied to acquire auditory geographic information (i.e. street/POI name) on the iPad device (Q2: M = 4.5, Q4: M = 5.0 and Q7: M = 5.0) than the two others. In addition, they responded that they were able to find out the long routes on the HBMap system (Q8: M = 4.0) the most easily.

Furthermore, the non-parametric Wilcoxon rank-sum test (at the 95% confidence level) is employed to compare the participants' rating on the three platforms. There are no significant differences between the HBMap system and the swell-paper maps on the eight questions. Apart from obtaining street/POI names (Q2, Q4 and Q7), it was found that the iPad platform has a significant effect on both the HBMap system and the swell-paper maps while following streets (Q1), locating POIs (Q3, Q6) and finding short routes (Q5). Since only three subjects finished the task for building long routes on the iPad platform, the result of the Q8 was not included.

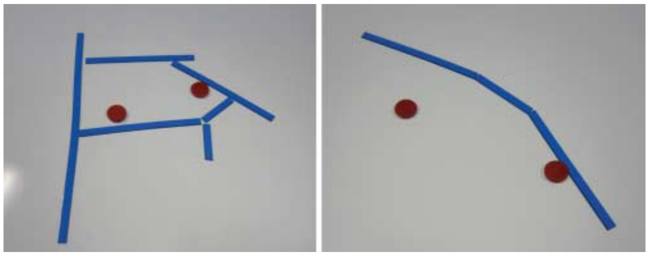

Figure 12. Building short routes with magnetic materials for Map 2 (left: a correct one by P3; right: an incorrect composition by P6) (The strips for streets, and the dots for starting/ending points.)

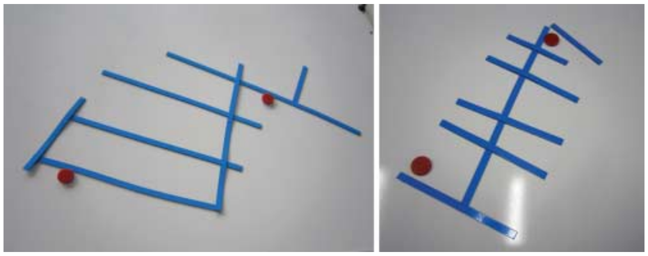

Figure 13. Building long routes with magnetic materials for Map 1 (left: a route close to the correct one by P1; right: an incorrect composition by P8).

4.4.8. *Results of the post-questionnaire*

With regard to the results of the post-questionnaire, nine subjects took part in it, excluding P10 who had a personal urgent appointment, and P7 who did not comment on Q11 since she did not do the tasks involved. Figure 14 introduces the participants' ranking distribution on the three platforms for Q9–Q12. The three platforms have a close distribution on acquiring geographic information (Q11), but most of the subjects thought the iPad platform was the worst one while following streets (Q10) and locating POIs (Q11). In summary (Q12), 66.7% of the subjects seemed to prefer their familiar swell-paper maps, and 33.3% thought the HBMap was the best. Additionally, all subjects reported that the iPad-based maps were worse than the swell-paper maps and the HBMap system.

When outlining the advantages and disadvantages of reading maps on the iPad platform, on the one hand, they expressed that it not only provides an easy way to speak out the geographic information, e.g. the names of streets/POIs, but it is also possible to access interactive maps while on the move. On the other hand, it is too hard to follow streets and locate POIs quickly while touching the smooth surface of the iPad device. Moreover, they had impressive experiences with the proposed HBMap system, such as the tactile map symbols, the interactive map operations (e.g. panning and zooming) and the applicable audio-haptic representation. Through the raised pins, they could not just follow streets but also find out the shape of intersections. At the end, they pointed out a series of solutions to improve the HBMap system, like defining more zoom levels, getting street/POI names without pressing a physical key, and speeding up the whole system.

4.5. Discussion

Compared with the audio-haptic paper-based tactile maps, the proposed HBMap system can be easily extended to represent any city maps by importing the involved map database and

Table 4. The mean error rate (%) of subjects' composition for building street maps.

Platform	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Mean
M1	60	50	13	50	42	35	87	51	37	90	51.5
M2	—	—	24	63	60	—	97	70	52	—	61
M3	39	65	28	44	41	48	82	54	40	59	50

Table 5. The mean error rate (%) of each criterion of short routes for M1 and M3.

Platform	d_1	d_2	d_3	d_4	d_5	d_6	Total
M1	4.9	1.2	0	6.8	0.9	0.4	14.2
M3	5.1	1.2	0	7.1	6.4	2.4	22.3

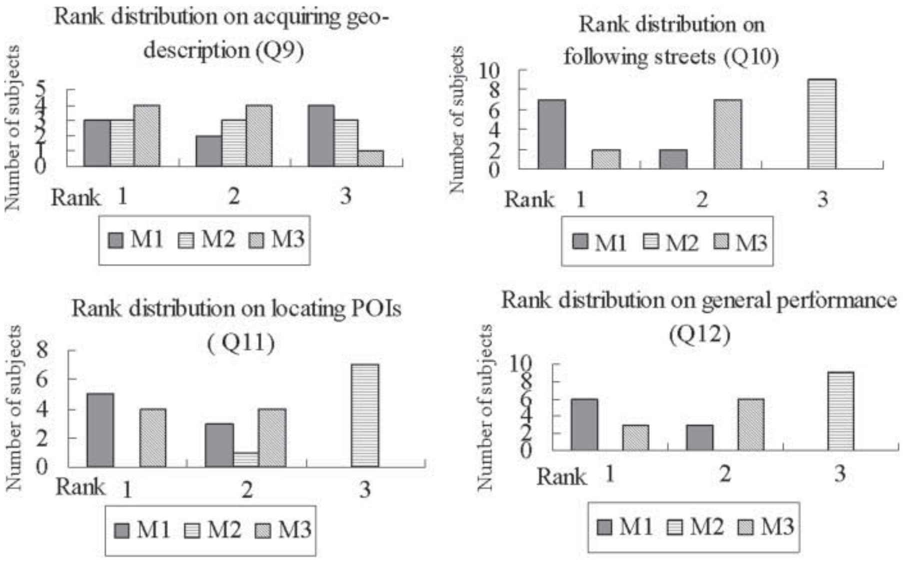

Figure 14. The platform rank distribution on Q9–Q12.

without manually producing paper-based tactile maps. With regard to the huge challenges involved in developing robust and accurate image-processing methods to render tactile city maps consisting of various POIs and irregular streets, the solution of processing GML-based vector map data should be a promising method that can be used on different platforms including common flat touch-screen devices. It is possible to apply other types of vector map data, such as Keyhole Markup Language (KML). Meanwhile, the methods proposed to render maps with tactile map symbols can be applied to other types of pin-matrix displays as well, apart from the HyperBraille display.

When developing a tactile map for the visually impaired, we need to consider their preferences and map-reading skills. Since in the orientation and mobility (O&M) training, individuals with visual impairments are taught to use a traditional tactile map (e.g. a swell-paper map or a thermoform-based map), and most of them are used to reading maps with both their hands (Blasch *et al.*, 1997). It is important to implement a feature that allows users to explore maps with two hands simultaneously. Furthermore, future O&M training might teach how to use an interactive map application that supports panning, zooming and other operations, like the HBMap system.

To compare performances on exploring accessible maps through different platforms, a method was applied to produce zoom-enabled and panning-enabled swell-paper maps in the involved evaluation. Since most of the participants were familiar with swell-paper maps, they did not have trouble in reading these maps, although some of them had problems while compositing maps with magnetic materials. However, they reported that they had to align the POI view maps piece by piece while zooming and making a long route, which required extra cognitive loads. Importantly, in practice, due to time and cost factors, it seems impossible to produce zoom-enabled and panning-enabled worldwide maps through the proposed method manually. But the HBMap system has made it possible to represent city maps in large-scale areas easily, with zooming and panning interactions. Furthermore, although two-thirds of participants preferred the swell-paper maps having only two zoom levels, it becomes more difficult to read swell-paper maps with three or more zoom levels, to align more than four sub-maps.

The participants were most unsatisfied by using the iPad platform to explore city maps. In total, only three of 10 participants finished all the tasks. Owing to the lack of tactile feedback, most of them had to give up on the tasks of preparing pre-journey routes after a large amount of effort, as they said that it was difficult to locate the POIs and follow the streets. From the evaluation, the participants were satisfied with the instant auditory feedback while touching map elements on the iPad. It is to be noted here that we developed the iPad-based prototype for the evaluation without a remote server. However, most real map applications have remote servers to process requirements, and this will delay the audio information after touching the map, in practice. The unexpected delay would lead to users learning incorrect information, as under such conditions the auditory output does not match the point contacted by the moving finger. It will be very important to find a solution to reduce the impact of unexpected delay while getting auditory information in real map applications. For the three participants who had finished all of the tasks, by comparison with the swell-paper maps and the HBMap system, they had to spend considerably more time on finishing the tasks on the iPad platform. It seems the regular flat touch-screen devices are appropriate for developing eyes-free navigation applications, which do not need too much map exploration. Perhaps future electrostatic touch displays with better tactile sensitivity will improve the involved performances on exploring maps. Meanwhile, it might be valuable to develop a solution for the iPad platform that actually provides audio and tactile feedback, such as attaching extra vibrators in the SpaceSense system.

More importantly, as a new map application, the proposed HBMap system has obtained a number of participants' approval, thanks to its audio-haptic representation, tactile map symbols and interactive functionalities. Even if most of them had had only a few experiences on pin-matrix displays beforehand, they quickly learnt the required skills to explore maps and prepare pre-journey routes on the HBMap system independently. The accuracy of building overview street maps and pre-journey short routes on the HBMap were similar to using the swell-paper maps, which they utilized for years. Their performances on the HBMap might be better once they acquire more skills and experience after long-term uses. Furthermore, participants can more accurately make long routes on the HBMap than on swell-paper maps, since its convenient panning operation does not require too many extra cognitive loads for aligning maps.

Due to the low tactile resolution of the HyperBraille display compared with the swell-paper maps, the HBMap system is less accurate for learning the exact street shapes and directions (see d_5 and d_6 in Table 5). Thus, it is necessary to improve the features in the future, such as by employing a pin-matrix display with higher resolution. The subjects complained about the additional effort required for panning, as they had to move one hand away from the map and press a button by the other hand, while acquiring auditory information. It might be helpful to develop an easy way to get instant auditory information, like on the iPad platform. But the time delay effect should be taken into account as well. Additionally, the tactile map symbols, as one of the most important parts, should be given more attention, not only focusing on extending the number of legends, but also considering how to standardize map symbols as an important user requirement for tactile maps (Rowell and Ungar, 2005).

As there were 10 visually impaired participants who joined the evaluation, the statistical results generated by such a small sample size are limited in terms of being able to draw scientific conclusions, particularly the results of building long routes by only three participants on the iPad medium. A further study with more users should be considered.

5. CONCLUSION

In order to allow visually impaired and blind people to explore worldwide street maps and to prepare pre-journey routes independently, we have proposed and implemented a pin-matrix display-based map system, namely HBMap. The audio-haptic HBMap has a typical Client/Server structure where the server manages map data and the client represents vector-based map data non-visually through raised or lowered pins. A set of tactile map symbols has been proposed to render the varying map elements, e.g. streets, bus stops, etc. In addition, the HBMap consists of a series of interactive map operations to allow users to explore conveniently, such as panning, zooming and searching.

In this study, 10 blind subjects were recruited in the evaluation of the HBMap system, in which we compared participants' performances in reading street maps and preparing pre-journey routes via three different platforms: swell-paper maps, touch-screen-based maps and the HBMap. The evaluation found that most of the subjects were able to explore street maps and preparing pre-journey routes on the HBMap system independently via interactive map operations (i.e. zooming and panning), and they had similar performances on the swell-paper maps and the HBMap system while exploring without panning and zooming. However, participants performed the panning and zooming operations better on the HBMap system than on swell-paper maps, in particular for preparing a long route which needs zooming and panning. After long-term usage of the HBMap system, users might perform better. Even if two-thirds of participants preferred the swell-paper maps with only two zoom levels, it becomes more difficult to handle with such maps with more zoom levels. In addition, most of them did not success in reading maps and preparing routes on the touch-screen-based map platform, due to the lack of tactile feedback.

A series of improvements should be considered as well. For instance, the current set of tactile map symbols could be extended by importing many more geographic categories, like symbols for various areas of interest (e.g. lakes and forests). The searching POI function should be evaluated in a future study with blind persons, to investigate whether the function would support the usability of the HBMap. In addition, the zooming interaction needs further study to investigate how the visually impaired learn from zoom-able tactile maps effectively.

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