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Audio-Vibratory You-Are-Here Mobile Maps for People with Visual Impairments

ELEN SARGSYAN, University of Toulouse 3, IRIT, France
BERNARD ORIOLA, CNRS, IRIT, France
MARCOS SERRANO, University of Toulouse 3, IRIT, France
CHRISTOPHE JOUFFRAIS, CNRS, IPAL, Singapore and CNRS, IRIT, France

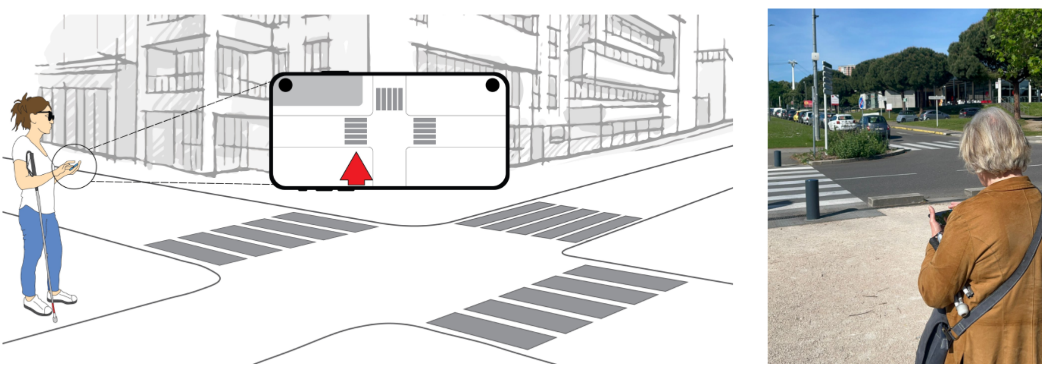

Fig. 1. Left: Illustration showing a person with VI in front of a crossroad and holding the audio-vibratory YAH map mobile device. Right: Photo of a participant with VI using the smartphone based prototype during the on-site evaluation.

Self-localization and wayfinding are challenging tasks for people with visual impairments (PVIs), severely impacting independent mobility. Visual "You-are-here" (YAH) maps are useful for assisting local wayfinding of sighted users. They are used to self-localize and display points of interest, landmarks and routes in the surroundings. However, these maps are not always available and rarely accessible to PVIs. Relying on an iterative participatory design process with eight end-users with visual impairments, we created a proof of concept of a mobile audio-vibratory YAH map. Our design is based on either a tablet or a smartphone to ensure a small and portable solution. A user study with ten PVIs showed that the audio-vibratory YAH map that we designed provides the user with a good understanding of the surroundings and wayfinding cues. Surprisingly, the results show that the audio-vibratory YAH map prototype was as usable as the control condition (audio-tactile YAH map with a tactile overlay), with similar user satisfaction and cognitive load. A follow-up field study with two participants showed the effectiveness of the prototype for assisting in crossroad understanding. To conclude, our innovative design of a mobile audio-vibratory YAH map can overcome the portability and printing issues associated with tactile overlays and can be an appropriate solution for assisting the pedestrian navigation of PVIs.

Authors' Contact Information: Elen Sargsyan, University of Toulouse 3, IRIT, Toulouse, France, elen.sargsyan@irit.fr; Bernard Oriola, CNRS, IRIT, Toulouse, France, bernard.oriola@irit.fr; Marcos Serrano, University of Toulouse 3, IRIT, Toulouse, France, marcos.serrano@irit.fr; Christophe Jouffrais, CNRS, IPAL, Singapore, Singapore and CNRS, IRIT, Toulouse, France, christophe.jouffrais@cnrs.fr.

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CCS Concepts: • **Human-centered computing → Accessibility systems and tools**.

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1 Introduction

You-are-here (YAH) maps are fixed reference maps strategically located in the environment, featuring a symbol to indicate the user's current location (self-localization) and assisting with local orientation and spatial cues [29]. They are used in complex areas and intend to ease wayfinding [27, 29]. They can assist in different cognitive processes important in wayfinding, such as self-localization, orientation and route selection. The utility of YAH maps is verified if a number of rules are respected: they must be located at decision points where people need assistance and should contain architectural elements and labels (e.g., buildings' or streets' names and numbers) so that the user can relate the environment to the map [27, 30, 32].

YAH maps can be of great interest to PVIs who struggle with self-localization and wayfinding [32], because they provide faster and more accurate self-localization compared to regular maps [35]. In-situ placement and alignment of YAH maps within the environment are key features for their effectiveness in orientation and wayfinding [29].

Terminals with adapted tactile YAH maps can be placed at some locations, such as train stations or museums, but they are rare and eventually difficult to locate for PVIs. YAH maps terminals (sometimes called kiosks) cannot be placed in challenging situations for PVIs, such as crossroads for instance. Numerous tools have been developed to aid PVIs in cognitive mapping and wayfinding, primarily when preparing a journey. Tactile maps – e.g. raised line maps on paper sheets – can assist cognitive mapping at home or school [39], but they cannot be used as mobile YAH maps because they are bulky, non-updatable, and require a prior decision on where to display the YAH symbol. Some mobile systems [5] can assist in for on-site wayfinding and obstacle detection by relying on audio, tactile, or vibratory feedback but lack the YAH map functions.

Weber *et al.* [45] presented a mobile audio-tactile YAH map system for PVIs based on an actuated pin-matrix display. The participants were able to effectively use the system after a short training period, successfully self-localizing and identifying surrounding streets and nearby points of interest. However, the authors pointed out that the lack of portability of the prototype was a significant limitation, suggesting that future studies should focus on enhancing the system's portability by employing embedded systems. Building on this insight, our study aimed to address the portability issue while maintaining all the functional aspects of a YAH map, ensuring that users can have a seamless and practical wayfinding experience. In this study, we relied on a participatory design process to create accessible digital mobile YAH maps for PVIs. Our aim was to design and evaluate an audio-vibratory prototype based on widely used devices (tablet or smartphone), which does not require a tactile overlay (e.g. raised-line map) and provides the VI user with an adapted YAH map that is generated on the fly, at their current location. In this study, we focused on crossroads because they present a challenging task in pedestrian navigation [3].

Our study included eighteen PVIs who participated in either the participatory design or the final evaluation of the device. The participatory design process involved eight participants and consisted of two main phases: observing user experiences with interactive maps of varying sizes and integrating end-users' design preferences into a prototype. We then conducted a user study with ten participants to compare two mobile audio-vibratory (AV) YAH maps (displayed on a tablet or a smartphone) to a control condition based on an interactive audio-tactile (AT) YAH map with a tactile overlay. The results show that the AV-YAH maps provided effective understanding of the crossroad and helped find a path to the destination. Contrary to our hypothesis, the AV-YAH map, appeared to be as efficient and satisfying as the AT YAH map with the physical tactile cues. A follow-up study with two participants in a real-world crossroad further supported the usability of the AV-YAH map for understanding and navigating unfamiliar crossroads.

Our contributions are: 1) the design of audio-vibratory YAH maps for mobile devices, 2) an evaluation demonstrating that these mobile audio-vibratory YAH maps are usable in terms of efficiency, cognitive load, and user satisfaction, and 3) evidence showing that small - e.g., smartphone size - audio-vibratory YAH maps are usable in a real-world environment.

2 Related Works

2.1 Navigation Aids for People with Visual Impairments

Independent navigation is a challenging task for PVIs [12]. In addition to immediate sensing related to mobility (obstacles and paths), PVIs need to know about landmarks and routes that sighted people can easily get by sight [2, 41]. Raised-line and 3D-printed maps [34] can assist PVIs in cognitive mapping and wayfinding, but they are cumbersome and impossible to update on the fly. They are mostly used at home or at the education center to prepare for a journey.

Various assistive technologies have been proposed for independent mobility and orientation [5]. Based on different sensors (cameras, ultrasounds, beacons, etc.), these devices can assist in wayfinding and obstacle detection. For instance, BlindSquare [1] and Lazarillo [2] are adapted commercial applications for assisting navigation. BlindSquare can display the direction of the user as well as information about the surroundings. Similarly, Microsoft Soundscape [3] provides the user with 3D audio cues to improve awareness about the surroundings. Lazarillo provides turn-by-turn guidance.

Their usability and utility have been demonstrated [6, 13, 36]. However, they cannot be used as a mobile YAH map to understand the surroundings, and it is difficult to get a mental image of the surroundings using it. But, obviously, the design of adapted mobile YAH maps could build upon these mobility and orientation assistive devices.

2.2 Tactile and Audio-Tactile Maps

The transformation of visual information into tactile information is usually made by experts and relies on rules and recommendations (e.g., BANA). Recent studies provide additional guidelines regarding the production of adapted tactile maps [20, 21]. Among the most important guidelines, the map should contain only essential information and avoid clutter. Different areas of the map should be easily distinguishable by touch to prevent confusion. Consistency - meaning the same symbol should consistently represent similar features across different maps - and discriminability of the symbols are also crucial.

Interactive audio-tactile maps are devices where a tactile map is overlaid on a touchscreen. Verbal descriptions are triggered when the user touches points of interest on the tactile map. Several authors have shown that interactive audio-tactile maps are useful for spatial learning [1]. Brock *et al.* showed that interactive audio-tactile maps are more efficient (shorter learning time), with improved usability and user satisfaction when compared to regular raised-line maps with braille

[1] https://www.blindsquare.com/about/
[2] https://lazarillo.app/theapp/
[3] https://www.microsoft.com/en-us/research/product/soundscape/

legends [8]. Similarly, Griffin *et al.*, compared cognitive mapping between a regular tactile map and an audio-tactile map, and their results were significantly better with the audio-tactile map [18]. Another study showed that more than half of 22 participants can describe a location after the exploration of an audio-tactile map [31].

Overall, tactile and audio-tactile devices have important limitations for real setting navigation. They are cumbersome and difficult to use on-site because they rely on a tactile overlay that must be prepared in advance. In addition, they cannot be updated easily, which means that the user must prepare and print several overlays for each journey. In addition, the user should precisely know the location where to put the YAH symbol and should be able to reach that location in the real settings before exploring the YAH map. Given these reasons, it is not reasonable to consider interactive audio-tactile maps with a tactile overlay as a viable solution for providing real settings YAH maps.

A prototype of audio-tactile YAH map for PVIs has been introduced by Weber *et al.* [45]. The system was based on an actuated pin-matrix array that displays map elements, as well as the user's updated location and heading direction. The device can be used with a mobile phone or a Wiimote cane, which provides audio feedback regarding nearby streets and points of interest when the user touches the corresponding symbols on the display. The on-site evaluation with eight legally blind and eight blindfolded participants showed promising results: the participants were able to locate themselves and understand an unfamiliar environment. Although promising, the device is not commercially available. Indeed, it is weighty and relies on an expensive technology. In addition, it is bulky and can hardly be used in real settings. Finally, contrary to the smartphone, it is a device dedicated to only one usage, which is a PVI's concern.

2.3 Audio and Vibratory Feedback when Exploring Digital Drawings with the Fingers

Tactile drawings with raised lines are widely used by PVIs because they provide rich and efficient tactile cues when exploring maps and graphics. However, tactile feedback is not the only feedback that can convey graphical information during finger-based exploration. For example, Zhao *et al.*, have designed an on-hand vibrotactile interface that can improve the exploration of digital drawings [46]. VibHand extends regular tablet vibrations by incorporating directional and progression cues through four vibrators positioned on the back of the hand. The user study showed an improvement in terms of speed and accuracy of digital graphic exploration with VibHand compared to tablet vibration only. Bardot *et al.* have designed another technique to explore a virtual map based on audio and vibratory feedback from a smartwatch [4]. Tennison *et al.*, showed that accessing and navigating graphical information through a touchscreen was more efficient and preferred to tactile prints [38]. In a comparative study of different feedback (audio only, audio and tablet vibration, audio and ring vibration), Adams *et al.* showed that the combination of audio and tablet vibration leads to the best performance in the evaluation of directions and distances [1]. Giudice *et al.* have shown that an audio-vibratory interface is a viable multimodal solution to support spatial learning and provide access to dynamic visual content [17]. Indeed, in a comparative study between vibro-audio devices and tactile documents, bar graph comprehension, pattern recognition and shape discrimination reached similar performances. In another study, Giudice *et al.*, compared spatial knowledge transfer to on-site navigation between audio-vibratory and audio-tactile maps [16]. The results observed on a spatial task show that audio-vibratory maps can support spatial learning and navigation. Su *et al.* also showed that audio feedback is useful for guiding PVIs' finger on a tactile screen and can help to effectively convey complex geometry [37].

All these studies show that audio and vibratory feedback could be an appropriate solution to design mobile YAH maps generated on the fly.

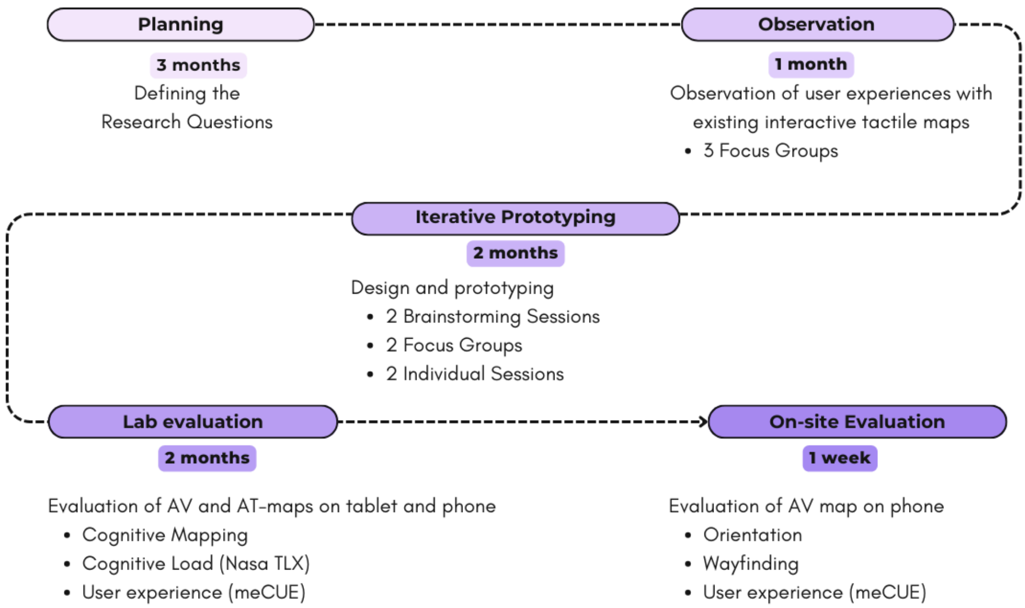

Fig. 2. Main steps of the participatory design process.

2.4 Research Questions

PVIs face challenges in independent navigation that require more than obstacle detection. They need spatial information about their surroundings, including the localization of landmarks and routes. Regular raised-line maps can provide this spatial knowledge but they are not adapted to on-site navigation. Navigation technologies can provide turn by turn assistance but are not designed to assist in building a mental map of the surroundings. Relying on the effectiveness of audio and vibratory feedback displayed on mobile devices, we aimed to design an innovative portable YAH map that can be displayed on the fly, when reaching a difficult place such as a crossroad. In this study, targeting this goal, we defined the following four research questions:

- RQ#1: How to design an AV-YAH map for PVIs displayed on an on-the-shelf mobile device?
- RQ#2: Can an AV-YAH map be usable for cognitive mapping of unfamiliar environments?
- RQ#3: Is there a size effect on AV-YAH maps, i.e. can a phone-size mobile map be as acceptable and efficient as a tablet-size mobile map?
- RQ#4: Can an AV-YAH map prototype be usable in real settings?

3 Participatory Design of a Mobile AV-YAH Map

During the participatory design, we addressed RQ#1 on how to design an AV-YAH map for PVIs relying on an on-the-shelf mobile device. Our final goal was to create a prototype that: i) can easily be carried onsite (smartphone or tablet), ii) is usable when exploring with the fingers, and iii) can assist PVIs to self-localize and get spatial information related to the immediate surroundings (e.g. when facing a crossroad).

Interactive audio-tactile maps are useful for PVIs in getting spatial knowledge independently, and they are more and more adopted in special education centers as teaching tools [9]. Thus, we started by observing the different usages and experiences of PVIs using interactive audio-tactile maps of various sizes. For this purpose, three focus groups were conducted with eight participants.

Then, we organized iterative design sessions including two brainstorming sessions, two focus groups and two individual sessions with two end-users.

3.1 Participants

In total eight participants were recruited. Tactile reading expertise was subjectively evaluated by the participants according to their experience with tactile documents. Participants who asserted they had no prior experience reading tactile documents were categorized as novices. Those who reported using tactile documents were classified as experts.

Table 1. Details about the focus groups (FG) and individual session (IS) participants (age, M=49.9, SD=16.9). The visual status is defined according to the World Health Organization classification of vision impairment (VI). Each focus group included one blind HCI researcher and one or two sighted HCI researchers.

Participant ID	Age	Gender	Visual Status	Tactile Reading Expertise	Focus Group
P1	52	F	Severe VI	Novice	FG1
P2	54	M	Blindness	Novice	FG1
P3	49	M	Blindness	Novice	FG1
P4	35	F	Severe VI	Novice	FG2
P5	50	M	Blindness	Novice	FG2
P6	19	M	Blindness	Novice	FG2
P7	69	F	Blindness	Expert	FG3,4,5 and IS1
P8	71	M	Blindness	Expert	FG3,4,5 and IS2

The research team involved four experts in Human-Computer Interaction (HCI), including one legally blind. This blind researcher is an expert tactile reader, frequently using tactile maps, and has contributed to several projects focused on the design of accessible maps for PVIs. His expertise played a significant role in informing the design process, ensuring that the needs and preferences of all the participants were carefully considered during the different steps of the iterative process.

3.2 Observation Phase

Our study started with observations in the special education center we collaborate with. The goal was to observe how PVIs use interactive audio-tactile maps, as well as individual differences related to their tactile reading skills.

3.2.1 Materials. The special education center uses interactive audio-tactile maps. They put raised-line graphics overlays on commercial tablets with a home-made software that we distributed freely. The software triggers audio sounds or verbal descriptions according to the finger's location on the drawing. Using this device, a user with VI can explore drawings independently and does not need to be a braille reader. They use A3 and A4 size maps. They never use smaller maps because teachers consider them as too small.

Tactile Maps. Crossroads are among the most critical steps during a wayfinding task. We prepared two audio-tactile maps representing a crossroad near the special education center (see Figure 3). The map content and styles were inspired by [21]. The maps show essential geographical information including streets, islands, pedestrian crossings, and buildings. They were printed on medium (22 cm x 14 cm, e.g. A4 like) and large size (A3) swell sheets.

Audio Interactions. We created a XML file describing the interactive zones and audio descriptions. The audio descriptions were inspired by [23]. As recommended by a tactile document maker, we added interaction points (empty circles) that are easy to locate by touch on all the essential elements

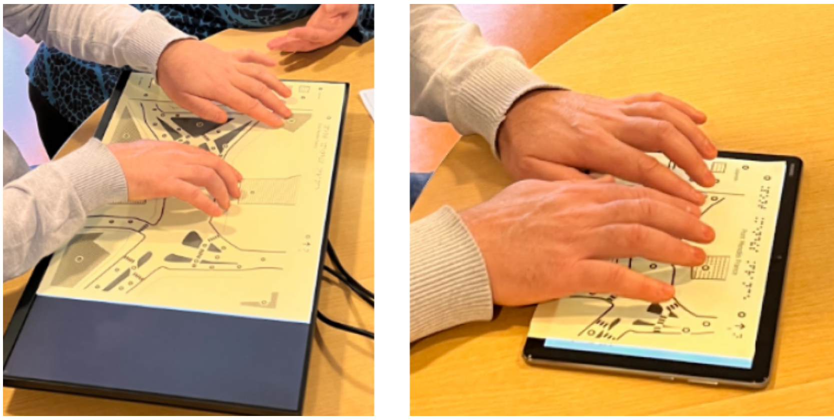

Fig. 3. P2 exploring an audio-tactile map of two different sizes: large tactile screen (A3 size) on the left and tablet (A5 size) on the right. The audio-tactile map is made of a tactile overlay placed over a touch sensitive screen or tablet. Audio descriptions are triggered when the user touches interactive zones of the tactile drawing.

of the map, as well as for the legend, title, and general description. The interaction points provide a general description of the map as well as information about the street names, pedestrian crossings (including accessibility features), surrounding buildings (including names of the shops in each building) and parks.

Devices. We used two touch sensitive screens with different sizes: i) a large one based on a Dell Flat Panel Monitor P2418HTt, and ii) a medium size one based on a Huawei Mediapad M5 Lite 09 tablet.

3.2.2 *Focus Groups with VI users.* FG#1-3 (see Table 1 for details about the participants) demonstrated that large audio-tactile maps are accessible to PVIs regardless of their tactile reading skills. In FG#1, novices were able to complete wayfinding tasks and identify essential geographical features. They also claimed to "understand the complexity of the crossroad" (P3) and "locate shops, buildings and pedestrian crossings" (P2). However, FG#1 and FG#2 revealed that novices struggled with smaller tablet-size maps. Despite these difficulties, P5 and P6 showed interest in audio-tactile maps if it could help them to know "Where I am". In FG#3, expert participants successfully completed tasks on both large and medium devices and expressed a preference for the medium size due to better portability and better efficiency. P7 said that the tablet size is "more portable and less cumbersome" and P8 that "it gives a better representation of the map".

In summary, the three focus groups indicated that large audio-tactile maps were generally accessible for PVIs, regardless of tactile reading expertise. On the other hand, medium-sized maps were deemed beneficial mainly for experienced tactile readers.

3.3 Iterative Prototyping Phase

As the large audio-tactile map could not be used as a portable device, we started designing a mobile AV-YAH map displayed on a tablet. According to the lessons learned in the previous workshops, this device would be more suitable for advanced readers. One of the challenges consisted in replacing tactile cues with vibratory cues. We recruited two participants (P7 and P8) and started an iterative design process with them, including two brainstorming sessions (BS#1-2), two focus groups (FG#4-5) and two individual sessions (IS#1-2) (see Figure 2).

3.3.1 Initial Design of the AV-YAH Map Prototype. We used the same tablet as in the previous sessions. The selection of map elements was made according to the limited space available on the tablet. We relied on the needs mentioned by Orientation and Mobility instructors when dealing with street crossing [40], with consideration to the available data on OpenStreetMap. Essential features for street navigation are streets, pedestrian crossings [40], traffic lights [14], buildings, grassy areas and sidewalks, as well as public transportation stops [14]. Their geometry must be simplified according to the BANA [7]. In order to create an interactive YAH map, we added two interactive points for the map description and orientation, as well as the YAH symbol. Table 2 summarizes all the YAH map elements.

Table 2. Tactile YAH map elements.

	Interaction Point	**Street**	**Pedestrian Crossing**	**Bus Stop**	**Building Blocks and Parks**	**Map Orientation Symbol**	**General Description Symbol**	**YAH Symbol**
Shape	Circle	Line on each side	Parallel rectangles	Solid Triangle	Parallelogram	Circle on the right side	Circle on the left side	Triangle
Filling Texture	Empty	Empty	Filled	Filled	Specific texture	Filled	Filled	Empty

We created a first prototype with an imaginary crossroad where all the tactile cues were replaced by vibratory cues (see Figure 4). The first informal tests with the blind researcher showed that finding an interactive point in an open area was difficult. Hence, we modified the map design by 1) removing interaction points in open areas, 2) triggering a continuous vibration while the finger is within an area, and 3) simultaneously triggering a single audio description (see Figure 4). We did additional informal tests showing that this prototype is more usable.

3.3.2 Iterative Design with PVIs. The first testing session aimed at: i) identifying different vibratory "textures" and ii) avoiding continuous vibrations that can be tiring. We tested several vibratory patterns, and we designed two maps with either discrete (Design 1) or continuous (Design 2) vibrations.

In FG#4, we compared the discrete and continuous vibrations with two users with tactile reading expertise (P7 and P8). Each of them had one tablet and was free to explore the interactive AV maps. After the exploration, we gave them the tactile maps corresponding to the explored AV maps. They had then to tell us whether the AV map provided a good mental representation of the crossroad. Both P7 and P8 provided encouraging and valuable feedback. P7 said "we need to focus more (than with the tactile map), but the AV map is completely understandable" and P8 said, "the AV map is understandable, but I would prefer to have different vibrations on different elements of the map". They both preferred continuous vibrations (Design 2). P7 said: "it's confusing when both the audio-description and the vibration stop, and you get no more feedback". P8 added: "we no longer know where we are". They also suggested adding a bracelet to hold the device when being on-site.

In FG#5, we created an AV map with distinctive vibratory patterns inspired from [25], and we added a bracelet to hold the device more easily (see Figure 5). The participants confirmed the importance of the bracelet and continuous vibrations. They paid more attention to the audio-descriptions than to the vibratory textures, which, finally, did not appear as mandatory to them.

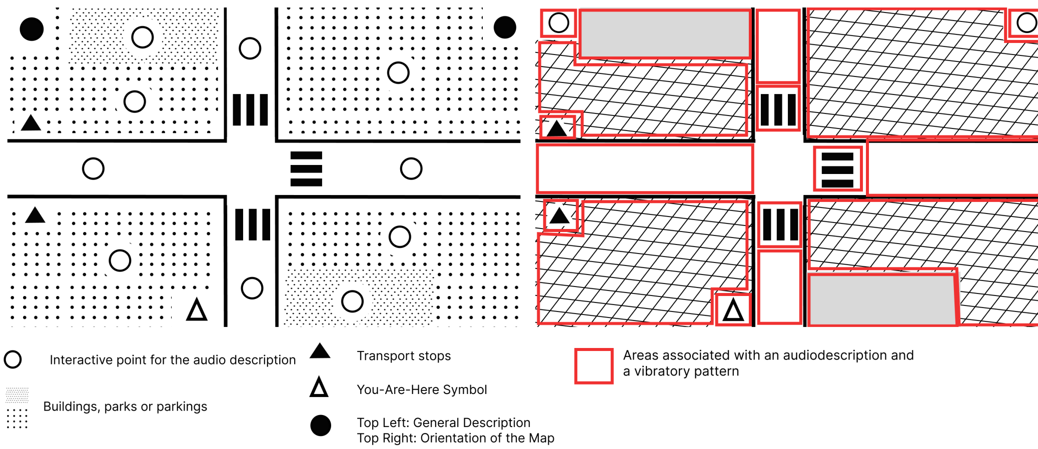

Fig. 4. Left: Example of an audio-tactile map printed on a raised-line paper sheet. Right: audio-vibratory map corresponding to the audio-tactile map on the left. The areas outlined in red are associated with a specific vibratory pattern ("vibratory texture") and audio description.

Finally, we organized two discussion sessions with P7 and P8 independently in order to prepare the comparative user study. During this session, they were free to explore the AV maps and they enjoyed the prototype. They easily answered spatial questions (e.g., locating points of interest, finding a path, answering orientation questions). Interestingly, P7 mentioned that she would like to have the same map on the smartphone because it is smaller, more manageable, and because "everyone has a smartphone now". We had the same discussion later on with P8, and he confirmed the P7 suggestions.

3.4 Summary of the Participatory Design Sessions

The observations made during the participatory design process showed that it is possible to design medium size AV maps that are usable by experienced tactile readers. Some users expressed interest in a smartphone size map because they already own a smartphone and because it would be easier to use onsite. This suggestion was contradicted by the tactile document maker helping in our study and having said that the smartphone size is too small.

We decided to include the smartphone size device in our study, and we designed a comparative study with three different devices: i) a medium size audio-tactile map (with a tactile overlay placed over the screen) as the control condition, ii) a medium size audio-vibratory (AV) map, and iii) a small size audio-vibratory (AV) map.

4 User Study

In this study, we addressed RQ#2 (Is an AV-YAH map usable for mapping an unfamiliar environment?) and RQ#3 (Is there a size effect on mobile AV-YAH maps, i.e. can a phone-size mobile AV-YAH map be as usable as a tablet-size mobile AV-YAH map?) Our study got approval from the university ethics committee (n° 2024_837).

4.1 Hypotheses

Because tactile maps provide cues that are easy to integrate, especially for PVIs with tactile reading expertise, we set up the following hypotheses:

- H1: The medium size AV-YAH map is usable (measuring efficiency, cognitive load and satisfaction).
  - H1.1: But less usable than the medium size audio-tactile AT-YAH map.
- H2: The small size AV-YAH map is not usable (or eventually less usable than the two other devices).

4.2 Participants

We recruited ten PVIs (Table 3) with tactile reading expertise subjectively assessed as good. None of them took part in the participatory design process. All of them gave their consent to participate to the study. They all use a long cane for mobility.

Table 3. Details about the participants (age M=56.7, SD=12.3). The visual status is defined according to the World Health Organization classification of VI. All participants use a long cane for mobility. None of them has a guide dog.

ID	Gender	Age	Visual Status	Assistive Device for Navigation	Street Navigation
SP1	M	64	Blindness	Google Maps	Independent
SP2	F	66	Blindness	None	Accompanied
SP3	F	63	Blindness	Apple Plans	Independent
SP4	M	56	Blindness	None	Independent
SP5	F	57	Severe VI	Google Maps	Independent
SP6	F	24	Moderate VI	Apple Plans, Moovit, Local Bus Application	Independent
SP7	F	52	Severe VI	Google Maps	Independent
SP8	M	64	Moderate VI	Cane with TOM POUCE® 3, Apple Plans	Independent
SP9	M	58	Blindness	None	Independent
SP10	F	63	Blindness	None	Independent

4.3 Materials and Methods

4.3.1 Interactive Devices. In this study, we compared three devices: an AT-YAH map as the control condition, and two AV-YAH maps with different sizes (see Figure 5). The first condition, called Audio-Tactile Tablet (AT-T), included a raised-line overlay placed over the touchscreen of a Huawei Mediapad M5 Lite 09 tablet (22cm x 14cm) with a 3D printed case to maintain the overlay over the screen. The second condition, called Audio-Vibratory Tablet (AV-T), was running on the same tablet, without any tactile overlay but with tablet vibrations. The users can hold the tablet on their forearm with a bracelet (see Figure 5). The Audio-Vibratory Smartphone (AV-S) condition was like the AV-T condition but with a smaller Samsung A32 smartphone (15.5 cm x 7 cm).

4.3.2 Maps. To ensure that the conditions are comparable, we created imaginary maps representing road intersections with the same elements and interactions but that were moved apart (see Figure 6). Each map contains six essential geographical data: streets, pedestrian crossings, transportation stops, buildings, green parks, and car parks. Three interactive symbols indicate the general description and the orientation of the map, as well as the YAH location. The maps fit the size of the devices, i.e., 22 cm x 14 cm for the tablet-sized maps, and 15.5 cm x 7 cm for the smartphone-sized maps.

We created 9 maps in total: three were used for the familiarization stage, and the other six for the test stage (i.e., one familiarization and two test maps per device). The crossroads contain three or four branches with thirteen or sixteen points of interest, respectively (see Figure 6). To avoid biases related to street names, we choose fictional names based on flowers (Tulip Street, Lilac Street, etc.).

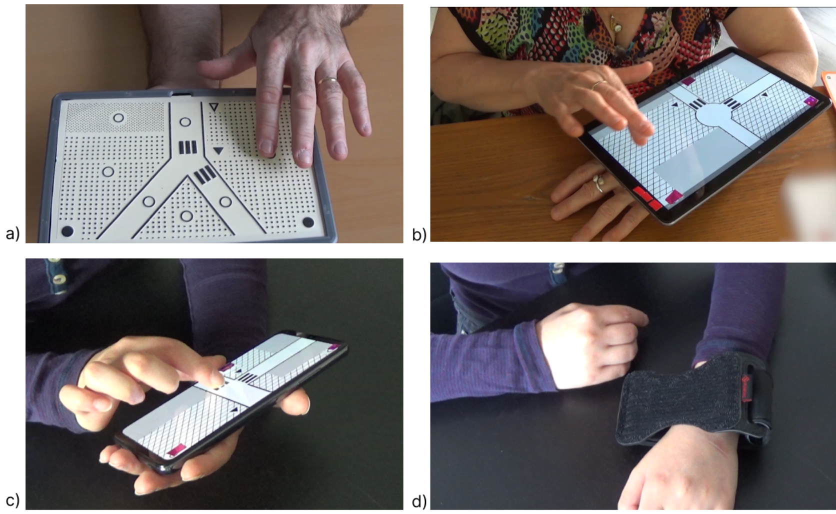

Fig. 5. a) Audio-Tactile Tablet (AT-T), b) Audio-Vibratory Tablet (AV-T), c) Audio-Vibratory Smartphone (AV-S), d) shows the adhesive bracelet placed around the forearm.

4.3.3 Interactive Audio Descriptions. Each element of the map was associated with a specific texture (tactile or vibratory) and an audio description (text to speech). The three interactive symbols were represented as tactile circles on the AT maps and stickers on the AV maps (see Figure 6):

(1) General description with the number of branches and the number of points of interest (POIs). For instance: "This map shows a T-like 3-branch crossroad. You can find 13 points of interest".
(2) Orientation symbol. For instance: " This map is oriented to the south ".
(3) YAH symbol allowing participants to find their current location on the map: “You are here”.

4.4 Design and Procedure

The study followed a within-subject design with three conditions (AT-T, AV-T, AV-S). The protocol consisted in three steps including: the familiarization, the evaluation of the three conditions, and the completion of two questionnaires (NASA TLX [4] and MeCue [5]).

4.4.1 Familiarization. During the familiarization phase, participants were introduced to each device. They were given five minutes to explore a map on each device and find ten points of interest. Then they were given five minutes for doing one wayfinding task per map. They were encouraged to ask questions if needed. During this stage participants felt more confident in using the prototypes.

4.4.2 Test. Participants did two tasks on each device.

Task 1: To find and verbally mention all the points of interest (thirteen or sixteen per map) within a 5-minute time limit. The task was considered as completed when all the points of interest were identified. We asked them to say the name of each element to make sure it was not an accidental touch.

[4] https://humansystems.arc.NASA.gov/groups/tlx/
[5] http://mecue.de/english/home.html

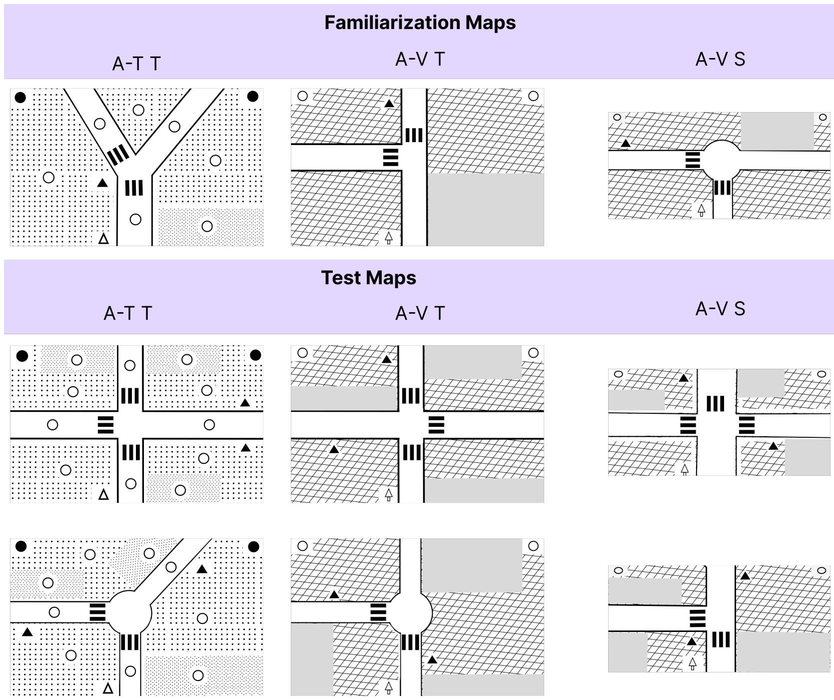

Fig. 6. The nine maps created for the user study.

Task 2: To complete two wayfinding tasks within a 5-minute time limit each. They were required to verbally describe and then use their finger to show the route from the YAH symbol to a specific destination (see Figure 7). In the example of Figure 7, the user must go from their actual location (YAH location) to the bus stop represented by the filled triangle. The instruction was that they can only cross the street using pedestrian crossings. To give a correct response, participants must mention the names of the street, as well as the names of the stores or building encountered on the way. A correct path description is illustrated here: *"To get from my position to the bus stop, I need to walk straight on Lilac Street until I reach the pedestrian crossing located on my right-hand side, which leads me in front the store. From there, I turn left, and then use the pedestrian crossing on Tulip Street. Then I turn left again and go to the pedestrian crossing on Rose Street. After that, I walk along the research lab, until I reach the bus stop."* If participants did not explicitly name all the landmarks, we asked them to tell the missing names.

4.4.3 Questionnaires. After the test phase, participants were invited to answer two questionnaires (NASA Task Load Index [15] and meCUE user experience [26]). The goal was to assess cognitive load, subjective usability, and user experience with the devices.

4.4.4 Other Collected Data. We obtained informed consent from all the participants to record the exploration session (audio and video of the hands). We measured the time participants took to complete each task, including finding points of interest and performing wayfinding. If the verbatims were not clear enough, we also asked open-ended questions after the test session. This qualitative feedback provided deeper insights into participants' perceptions, preferences, and challenges related to using each device.

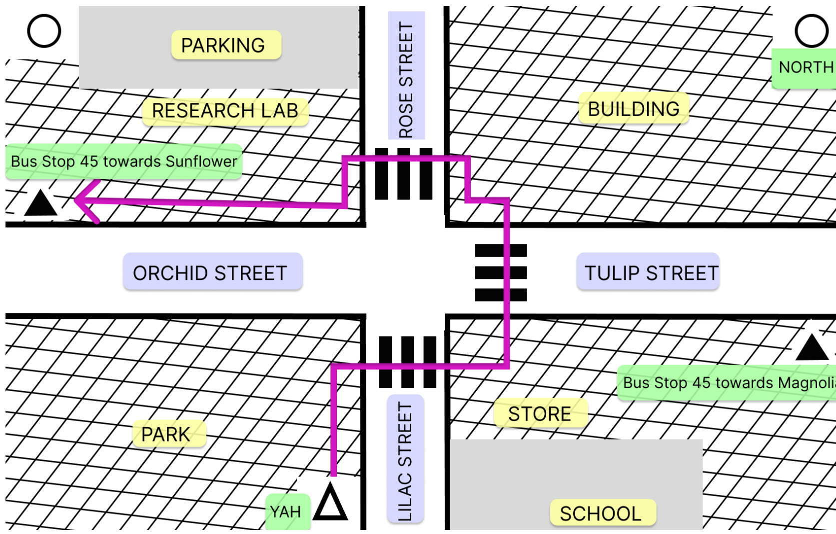

Fig. 7. Example of a wayfinding task. This YAH map represents a crossroad with four streets, six different buildings and three pedestrian crossings, with the YAH location (empty triangle) and destination (Bus stop, filled triangle). The correct path is illustrated in pink for illustration purpose.

4.4.5 Data Analysis. We used descriptive statistics with the mean values and 95% confidence intervals (see Figure 9, Figure 10, Figure 11 in Appendix). We verified the data distributions with a Shapiro-Wilk test. For normal distributions with homogeneous variances, we used parametric ANOVA tests. Otherwise, we used a non-parametric Friedman ANOVA. When necessary, we used post-hoc tests (Tukey HSD for normal distributions, or Wilcoxon pairwise multiple comparisons for non-normal distributions).

5 Results

5.1 User Performance

Task 1: All the participants were successful in locating all the points of interest in all three conditions. The average times for locating one POI were: AT-T (9.3s, CI: 7.3, 11.2), AV-T (10.7s, CI:7.6, 13.1) and AV-S (8.9s, CI:6.5, 10.9) (see Figure 8). According to the Shapiro-Wilk test, distributions were normal (AT-T: $W = .97$, $p = .85$; AV-T: $W = .9$, $p = .24$; AV-S: $W = .89$, $p = .18$). The Levene's test showed that the variances were homogeneous ($F(2, 27) = .38$, $p = .68$). The ANOVA did not show any significant time completion differences between the three devices ($F(2, 27) = 0.55$, $p = 0.58$).

Task 2: Except SP2, all the participants were successful in the wayfinding task with all the devices. SP2 did not successfully complete one wayfinding task [6]. Hence, we removed her data from the analysis on wayfinding completion time. The wayfinding times were: AT-T: 49.0s, CI: 37.9, 64.4; AV-T: 50.7s, CI: 38.3, 70.7; and AV-S: 40.9s, CI: 32.3, 51.6 (see Figure 8). According to the Shapiro-Wilk test, distributions were normal (Tactile: $W = 0.84$, $p = 0.058$; Tablet: $W = 0.85$, $p = 0.079$; Phone: $W = 0.88$, $p = 0.19$). The Levene's test shows that the variances were homogeneous across devices ($F(2, 24) = 0.24$, $p = 0.79$). The ANOVA test did not show a significant difference between devices ($F(2, 24) = 0.56$, $p = 0.57$).

[6] SP2 did not successfully complete at least one task on any device. We instructed participants to use pedestrian crossings when crossing streets. Regardless of this instruction, SP2 continued crossing the streets without using the pedestrian crossings

Table 4. Nasa and meCUE dimensions with no significant differences between devices.

NASA-TLX Dimension	Statistics (F for ANOVA and χ^2 for Friedman)	p-value	meCUE Dimension	Statistics (F for ANOVA and χ^2 for Friedman)	p-value
Mental	F (2,27) = 1.26	.3	Usefulness	χ^2 (2) = .66	.72
Physical	χ^2 (2) = 3.9	.14	Usability	χ^2 (2) = 2.74	.25
Temporal	χ^2 (2) = 1.28	.52	Commitment	χ^2 (2) = .62	.74
Effort	χ^2 (2) = 4.9	.08	Visual Aesthetics	F (2,27) = .02	.98
Frustration	χ^2 (2) = .55	.76	Status	F (2,27) = .01	.99
			Intention to use	F (2,27) = .019	.98
			Loyalty	F (2,27) = .21	.81
			Overall	F (2,27) = .05	.95

The results on tasks 1 and 2 confirm hypothesis H1 but do not confirm hypotheses H1.1 and H2. These results are surprising, considering the existence of tactile cues on the AT-T device and the tactile reading expertise of the participants. We expected a significant difference in favor of the audio-tactile maps. Although an absence of effect is not a significant result, it tends to show that users performed similarly with the audio-vibratory devices. Converging observations were made with the absence of difference between the success rate (correct answer rate) using each device. The Friedman test [$\chi^2(2)$ = 2, p = .37] did not show any significant differences (AT-T: 75%, [51.9, 98.1]; AV-T: 80%, [59.6, 100] and AV-S: 90% [79, 100]).

5.2 Cognitive Load and User Experience

In line with the results on performance, we did not find any significant differences between the three devices for the NASA-TLX dimensions [7] (see Table 4).

We found statistically significant differences between devices in **Positive** [F (2,27) = 4.57, p = .0195] and **Negative Emotions** [F (2,27) = 7.04, p = .003]. A Tukey post-hoc test showed a significant difference in Positive emotions between the phone and the tablets (AV-S vs. AV-T, p = .01; AV-S vs. AT-T, p = .01). Indeed, the participants found that medium size maps on tablets (AT-T, M=3.95 [2.95, 5.18] and AV-T, M=3.7 [2.75, 4.8]) induce significantly more positive emotions than the small map presented on smartphone (AV-S, M=1.97, [1.48, 2.65]). Coherently, the participants found that the tablet devices (AT-T, M=1.75 [1.33, 2.22] and AV-T, M = 1.9 [1.43, 2.3]) induce significantly fewer negative emotions as compared to the smartphone (AV-S, M = 3.4 [2.68, 4.55]). The Tukey post-hoc test confirmed the significant difference in Negative emotions (AV-S vs. AV-T, p = .005; AV-S vs. AT-T, p = .012). Thus, the maps displayed on a tablet are judged as more enjoyable than the maps on a smartphone. These results are not in line with the intention to use because five over eight participants said that they would prefer using a smartphone-based YAH map in real settings. More details concerning participants' feedback are discussed in the following section.

[7] More details on average scores with 95% CI for NASA TLX and meCUE are in Figure 10 and Figure 11.

5.3 Participants' Feedback

5.3.1 AT vs. AV Maps: Pros and Cons. Participants acknowledged the efficacy of the audio-tactile (AT) maps, but they are aware of their limitations and drawbacks. All participants recognized that AT maps are usable but noted their impracticalities. SP4 said, "I think relief brings a lot, but it's something that can't be carried on. You must be realistic." SP6 mentioned that the tactile maps have an added value, which is "to better detect outlines and feel shapes" but tactile maps have drawbacks because of the necessity to print the overlays. She added that AV maps can be used independently. SP3 raised concerns about the cost and unique usage of tactile maps. She mentioned the fact that tactile maps are expensive, and once she has used it, she not need it anymore: "It's a waste of paper". All participants except SP2 and SP10 considered using AV-YAH maps in real settings.

5.3.2 Tablet vs Phone Size: Pros and Cons. Preference for Tablet. SP5, SP6, and SP7 favored the tablet size YAH map for its practicality. SP5 said, "if I had to choose between the three devices, I would take the tablet for its practicality (in everyday setting)." SP6 explained, "it's very intuitive for all three devices, but I have a slight preference for the tablet". She explained that she has some experience with tablets" and she added, "you can have it with you all the time, you just open your bag and use it, I find it really convenient". It is interesting to note that SP5, SP6 and SP7 have residual vision.

Preference for Smartphone. SP1, SP3, SP4, SP8 and SP9 leaned towards the smartphone due to smaller size and convenience. Interestingly, all of them are blind except SP8. SP3 explained, "I prefer the phone because I'm blind and the tablet screen doesn't give me anything extra, my phone serves me for everything, and the size is large enough.". SP1 claimed that "the phone is the most convenient, we have it in our hands at all times ". According to SP4, "The tablet doesn't interest me because it's a much larger space to swipe on and, as a result, you have to make a greater effort". SP8 said, "I would take the phone to on-site navigation". He added: "The phone is smaller, the gestures are shorter, so the mental image is created more quickly". SP9 said: "At the end, I felt I was able to realize the tasks a bit better, I like the idea of the phone, it is less cumbersome". He also said: "I hesitate between the tablet and the phone, but I find the phone simpler". Although SP6 preferred the tablet, she mentioned that for everyday use, she would probably take the phone. SP7 also preferred the tablet; however, she added that the phone would be safer in the street because of its small size. SP7 expressed worries about the tablet's breakability. She said she would like to bring the tablet with her, but she added that "the phone would be safer" because the tablet can easily be "bumped". SP5 prefers the tablet, but she said that she would use the phone with a stylus. We gave her a stylus at the end of the experiment for testing on a new map. She said: "I need to get used to it, but it's even easier" compared to finger exploration. As previously mentioned SP5, SP6, and SP7 are users with VI whereas SP1, SP3, SP4, SP9 are legally blind. The preference for the tablet may be related to the fact that participants with VI can eventually use residual vision to help in reading the maps. Blind users feel that they can manage with their smartphone.

5.3.3 A Useless Challenge for Two Participants. As mentioned in the details (Table 2), SP2 does not have independent mobility. She is always moving with a human guide. She explained that she does not want to "clutter up" her life and prefers to prepare her journeys with someone.She explained that she is not using technologies a lot in her daily life. SP10 found all three devices challenging due to the use of a single finger for exploration. However, she acknowledged the potential value of the concept saying that: "The concept is good, it would be suitable for people who have a better spatial representation than me".

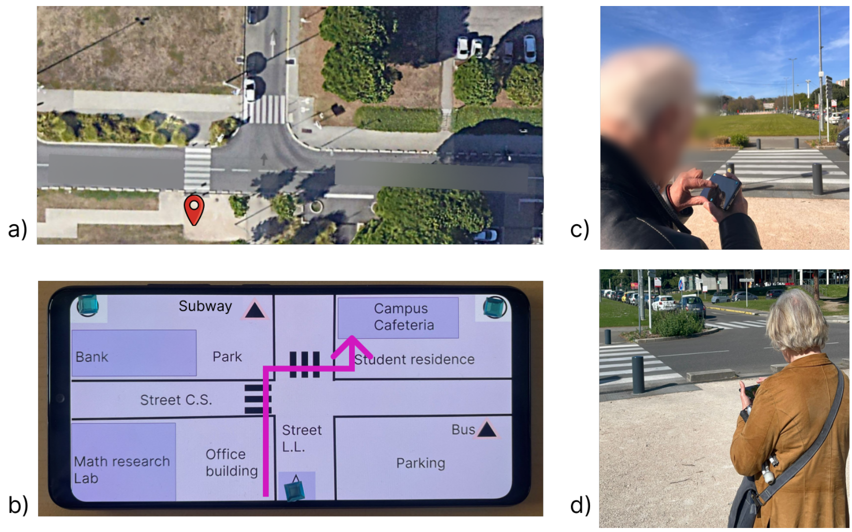

Fig. 8. a) The experimental location from Google Maps, b) The audio-vibratory map corresponding to the location on the phone, the path is illustrated in pink for illustration purpose, c) and d) participants exploring the map at the first YAH location.

6 Follow-Up Study in the Field

We conducted a follow-up study on the university campus with two participants, in order to address RQ#4 : Is an AV-YAH map prototype usable in a real-world setting?

6.1 Participants

As we did not need naive participants, we recruited participants SP1 and SP3 from the previous lab study based on their geographical proximity. They gave informed consent to participate in the study.

6.2 Materials and Methods

We selected a location on the campus that includes a crossroad with two pedestrian crossings, and which was not known by the participants (see Figure 8). We created two AV-YAH maps corresponding to the entrance of the two pedestrian crossings. To enhance the complexity of the map, we added fictive buildings and transport stations along the streets. The maps featured five buildings, one park, one car park, two transport stops, two pedestrian crossings, and two streets. We added the three interactive points providing a general description, orientation of the map and the YAH location. We used the same phone as in the lab conditions. The first author did the observations, and a human observer was present to ensure safety.

6.3 Experimental Protocol

The protocol included the following six stages: 1/ Reminder of the AV-YAH map device: Participants were free to explore another map before going on site. 2/ Onsite Crossroad Exploration: The participant was led to the location indicated by the YAH symbol and started to explore the map. Exploration time was not limited. 3/ Orientation Task #1: After the participant has explored the map, we asked questions about the location of elements. Without moving, they were asked to indicate their responses according to either cardinal directions (North, South, East and West) or clock face (e.g. 10am). 4/ Wayfinding task: Then, they were asked to verbally describe and do the route to the cafeteria (see Figure 7). This route includes two pedestrian crossings and two turns. 5/ Orientation Task #2: After having travelled the first crossing and first turn, while they were facing the second pedestrian crossing, we asked the same orientation questions again. If needed, the participants were offered a second map with the updated YAH location to verify their answers. 6/ meCUE survey: Back to the lab, we asked open-ended questions based on the meCUE questionnaire to gather detailed feedback on their experience.

6.4 Results

Table 5 summarizes the time spent on each task.

Table 5. Time spent on each task.

Participant	Time Reminder at Lab	On-site Exploration	Orientation Task #1	Wayfinding Task	Orientation Task #2	Overall Time
SP1	4 min	1 min	2 min 30s	3 min 20s	1 min 10s	12 min
SP3	6 min	5 min	8 min	1 min 30s	3 min	23 min 30s

6.4.1 Experimental Results. The participants answered orientation questions by referring mostly to the clock face and by pointing the direction with their hands.

SP1 was confident about his own answers and did not wish to explore the second map. He successfully answered all orientation questions and accurately completed the wayfinding task. He did not have any hesitations during the test.

SP3 initially struggled to orient herself using the phone, turning it around and expecting the map to update. We clarified that the map was only a static prototype and could not update in real-time. After being more confident in her own location, she waited for a passing car to check for the street orientation. Then, she successfully answered all the orientation questions and accurately described the path to the cafeteria. When reaching the second pedestrian crossing, she answered the orientation questions and checked the responses on the second map. She completed the wayfinding task without difficulties.

6.4.2 Participants' Feedback. Both SP1 and SP3 mentioned that the AV-YAH map is useful for understanding and navigating the crossing.

SP1 said that he would use the mobile AV-YAH maps if available, mentioning that learning about crossroads with this device would be very helpful. He mentioned that, when his sight was better, he was using visual printed maps while travelling. He considers that using this device in real-time when facing a crossroad would be a good option for travelling confidently and safely. He added: "We could replace the current apps with the AV-YAH map because the existing apps don't inform me if there's a bakery nearby. But with this map, I can discover all the surrounding elements".

SP3 said that AV-YAH maps could be very useful for traveling. She would use it if they were dynamically updatable.

7 Discussion

In this study we designed and evaluated a portable AV-YAH map for managing crossroads. Based on previous results in the literature, we had the hypothesis that participants would prefer audio-tactile maps and would perform better with them. Indeed, relying on the presence of tactile cues, the exploration of tactile maps can convey a good mental image of the drawing [13, 19]. Conversely, the absence of tactile cues when using audio-vibratory feedback makes tactile exploration and interaction with the device more challenging [43]. In addition, our participants are tactile reading experts, and we were expecting that they would prefer tactile maps and perform better on them because they are used to them.

However, the results do not show any significant differences in terms of cognitive mapping performance, between AV-YAH maps – whether on smartphone or tablet – when compared to the baseline audio-tactile YAH map. Our main objective in this study was not to show that AT-YAH maps are more efficient than AV-YAH maps, or the opposite. Indeed, because of the need of tactile overlays, AT maps are not usable during on-site navigation. Conversely, our main contribution is that AV-YAH maps displayed on tablets or smartphones are usable in real settings. These results are in line with [1, 4, 17, 33, 46], showing the efficiency of vibratory cues to understand virtual drawings. In [1], the results show that participants with VI can accurately locate points of interest on an audio-vibratory indoor map after a familiarization phase. In [33], authors designed a useful phone application to help PVIs in wayfinding tasks by guiding them with audio-vibratory feedback.

We found that the tablet-size AV-YAH map provided significantly more positive emotions and significantly fewer negative emotions compared to the smartphone-size AV-YAH map. This result is in line with [24], showing that the design of smartphone-based assistive applications is challenging because of the small size of the device and the lack of tactile cues or buttons. However, smartphone-based assistive technologies are emerging, and our participants highlighted the benefits of the smartphone. Interestingly, we observed that this preference could be related to the visual status. Blind users prefer the phone because it is easier to handle, and they cannot rely on residual vision to eventually read on the tablet screen. This question should be addressed in a future study.

After the promising results in laboratory conditions, we did a follow-up study to explore the effectiveness of the AV-YAH map in a real-world setting. This follow-up study was particularly important because the stress of navigating busy streets with traffic noise can potentially affect how well participants can use the AV-YAH map. The real-world test conducted on the university campus with two participants, showed that the AV-YAH map was considered as useful and efficient for understanding the crossroad with surrounding elements and identifying the path to a nearby location. This result is in line with Giudice *et al.* study showing that a tablet-size audio-vibratory map can support cognitive mapping [16]. The effective transfer of spatial knowledge observed in their study is encouraging, suggesting that after exploring the on-the-fly YAH map, mobility in the crossing could be performed safely and with fewer errors. Our study goes a step further by showing that even with a smaller, phone-size map, and without any verbal guidance from the researchers, participants can perform wayfinding tasks independently. This marks a significant advancement, suggesting that participants can rely solely on the map for navigation, enhancing their autonomy in real-world settings.

However, we observed that SP3 struggled with self-localization and expected the map to update dynamically. This observation shows the importance for interactive, updatable, YAH maps [5] and underscores the limitation of tactile overlays during on-site navigation. YAH maps should be created on-the-fly, dynamically and updated in real-time based on the user's location, similar to navigation applications.

8 Limitations

While our study found no significant differences between the AT and AV-YAH maps in terms of efficiency, this does not imply that they are equally efficient. An increased sample size might reveal significant differences. Nevertheless, our quantitative results suggest that AV-YAH maps are effective for spatial understanding and wayfinding without increasing cognitive load, subjective effort, or frustration. Even more interesting, our qualitative findings indicate a preference for AV-YAH maps among users, mainly because they are portable and they can have it all the time.

Our participatory design process included novice tactile readers. However, we finally focused on participants with tactile reading skills for the comparative study. This shift was due to the observation that novice tactile readers often struggle with interpreting small-sized drawings. It is crucial to recognize that the ability to read and understand raised-line graphics - including maps - is not an innate skill for PVIs [11, 36]. According to [11] "The maps reader must be trained to recognize and understand the relief material, the point and line symbols, the use of areal texture, and the use of the key that unlocks the information on a particular map. Various techniques can help train readers to use relief maps". As a matter of fact, proficiency in tactile reading is obtained through training and practice. Then experienced tactile readers exhibit significantly better tactile acuity compared to novices [42].

Our research goal was not to investigate the learning process of AV-YAH maps exploration. Instead, we focused on designing an AV-YAH map prototype based on existing mobile devices, considering the needs and preferences of the potential users. An alternative research question could be: How to design simple YAH maps that are accessible to novice readers? This question was out of the scope of our current study and could be addressed in a future work.

9 Conclusion and Future Works

Despite the availability of several commercial tools aiming at self-localization and wayfinding, such as Soundscape or Ariadne, significant gaps remain in their functionality. Soundscape helps localize POIs in the vicinity but does not provide an overall mental representation of complex places - such as road crossings - and its effectiveness in finding POIs was tested only with sighted participants [10]. Ariadne, while providing user location along with street and building numbers, lacks the precision of our YAH map, as it does not include the locations of crucial landmarks such as pedestrian crossings, building names or transport stations. The most comparable tool to date is an experimental device mentioned in [45], which has the disadvantages of a high cost and lack of portability. Future studies should conduct large-scale, in-field evaluations to compare the advantages of AV-YAH maps with existing technologies, such as Soundscape or Ariadne. Specifically, these studies should assess whether users can achieve the same level of spatial understanding and cognitive mapping with each of these devices. Such evaluations should also explore user preferences for haptic versus auditory feedback. If users can achieve comparable cognitive mapping across devices, preferences for feedback types could significantly influence the usability and adoption of these tools. Identifying these preferences and understanding their impact will provide valuable insights into how to enhance effectiveness and user satisfaction, and will also allow for the exploration of their complementarity

Our study introduces a new approach for creating on-the-fly AV-YAH maps that are usable by VI users. Such AV-YAH maps can convey spatial understanding about an unknown location and assist in navigating it. In terms of implementation, we relied on recent results regarding the automatic creation of adapted maps [21], augmented with audio descriptions [23]. Online services such as TMAP (Tactile Map Automated production), TMACS [28] (Tactile Map Automated Creation System), Mapy.cz, and others, rely on OSM data to generate tactile maps at various scales. These maps can include essential geographical information such as pedestrian crossings, streets, and buildings, as well as other important features for independent navigation such as transportation stations, urban furniture, etc. [21, 44]. A recent study shows that it is possible to create adapted maps of crossings with appropriate layout, elements and styles [44].

In addition to the automatic creation of the YAH maps, automatic creation of verbal descriptions has also been introduced by Kalsron *et al.* [23]. Interestingly, the authors envision the generation of located textual descriptions that can be integrated into a multimodal accessible map. With such a service, it is possible to create verbal descriptions attached to different locations on the map. Clearly, one could rely on all these new services to design audio-vibratory mobile YAH maps with verbal descriptions that are generated on the fly, according to the current location of the user.

Using on-the-fly YAH maps could empower PVIs when moving around the city, thereby improving independent mobility and hence inclusion. Future work may consider two aspects: the first one would be the integration of this concept into a smartphone application. Users could access it on demand, from any location and at any time. A real-life scenario would involve users stopping by when approaching a street crossing and switching from their traditional guidance app to the AV-YAH map app. They could then explore the crossing freely, instruct their path preference to the navigation app and restart independent navigation with better knowledge about the crossing. In our mobility scenario, the user travels with a turn-by-turn navigation app and can stop at any location, such as a complex crossroad, to open the YAH map app on their phone, which represents the scene in front of them. Thus the map respects a forward-up alignment [27, 29], similar to static visual YAH maps. As the user stands at the same location, the YAH symbol remains stable, but the map updates dynamically according to the compass orientation of the smartphone. This approach aims to make accessible mobile YAH maps similar to the physical YAH maps displayed on terminals. Such a scenario would improve spatial awareness and independent choices while decreasing inappropriate judgements and hazardous behaviors. This scenario is realistic considering the results of a large-scale analysis of data from the iMove app [22]. iMove is a mobile app that supports the orientation of PVIs, and the data contains millions of interactions by thousands of users over a year. The analysis shows that app users prefer receiving navigation notifications while moving but perform actions while stationary. The most common action is reporting the current address, highlighting the importance of the YAH spot.

Another application could be the development of a serious game allowing users to face challenging situations at home using their tablet or smartphone. In the game, they could face crossings of different complexities and answer questions regarding orientation, points of interest and wayfinding. Such a game would probably help to increase general navigation skills and decrease the stress before a journey.

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A Appendix

A.1 Mean Time Results

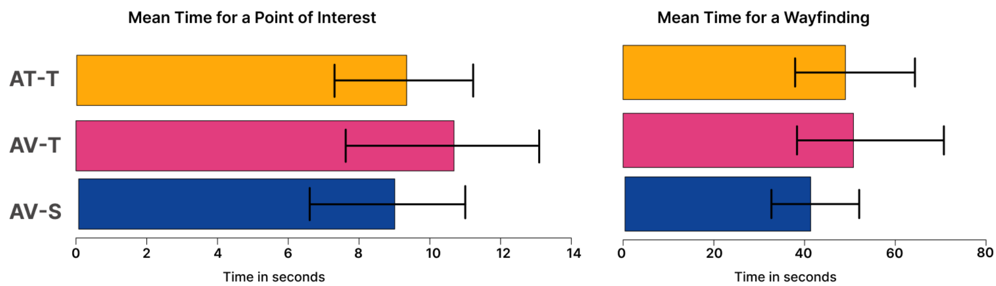

Fig. 9. Mean time to find one point of interest (left), and mean time to perform one wayfinding task (right), for each device (95% CIs).

A.2 NASA Task Load Index Results

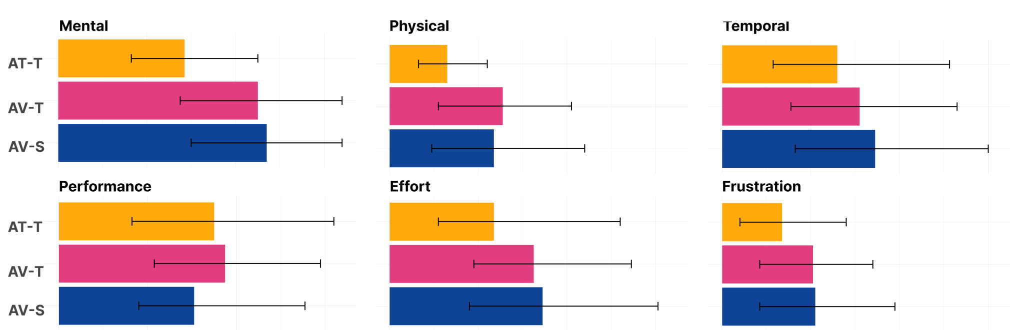

Fig. 10. NASA Task Load Index Results (from 0 to 100), for each device 95% Cis.

A.3 meCUE User Experience Results

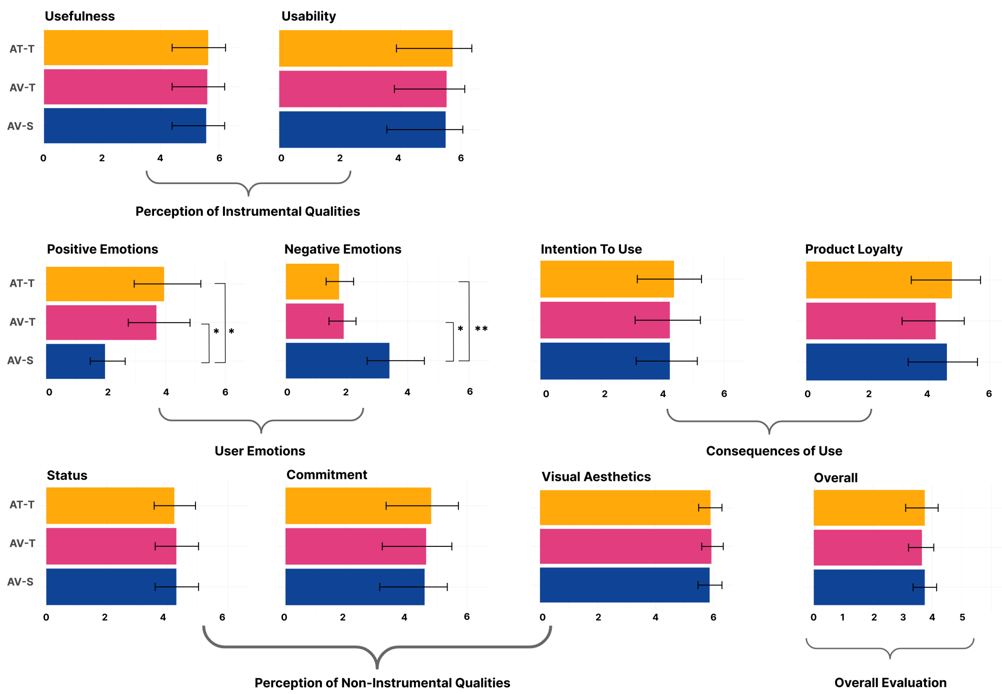

Fig. 11. meCUE user experience results. Significant differences are indicated with * ($p < 0.05$) and ** ($p < 0.01$).

References

[1] Richard Adams, Dianne Pawluk, Margaret Fields, and Ryan Clingman. 2015. Multimodal Application for the Perception of Spaces (MAPS). In *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility* (Lisbon, Portugal) *(ASSETS '15)*. Association for Computing Machinery, New York, NY, USA, 393–394. https://doi.org/10.1145/2700648.2811386

[2] Abdulrhman Alkhanifer and Stephanie Ludi. 2015. Disorientation Factors that Affect the Situation Awareness of the Visually Impaired Individuals in Unfamiliar Indoor Environments. In *Universal Access in Human-Computer Interaction. Access to the Human Environment and Culture*, Margherita Antona and Constantine Stephanidis (Eds.). Springer International Publishing, Cham, 89–100. https://doi.org/10.1007/978-3-319-20687-5_9

[3] Daniel H. Ashmead, David Guth, Robert S. Wall, Richard G. Long, and Paul E. Ponchillia. 2005. Street Crossing by Sighted and Blind Pedestrians at a Modern Roundabout. *Journal of Transportation Engineering* 131, 11 (2005), 812–821. https://doi.org/10.1061/(ASCE)0733-947X(2005)131:11(812)

[4] Sandra Bardot, Marcos Serrano, and Christophe Jouffrais. 2016. From tactile to virtual: using a smartwatch to improve spatial map exploration for visually impaired users. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Florence, Italy) *(MobileHCI '16)*. Association for Computing Machinery, New York, NY, USA, 100–111. https://doi.org/10.1145/2935334.2935342

[5] Raju Shrestha Bineeth Kuriakose and Frode Eika Sandnes. 2022. Tools and Technologies for Blind and Visually Impaired Navigation Support: A Review. *IETE Technical Review* 39, 1 (2022), 3–18. https://doi.org/10.1080/02564602.2020.1819893

[6] Mark Blades, Simon Ungar, and Christopher Spencer. 1999. Map Use by Adults with Visual Impairments. *The Professional Geographer* 51, 4 (1999), 539–553. https://doi.org/10.1111/0033-0124.00191

[7] Braille Authority of North America. 2024. Guidelines and Standards for Tactile Graphics. https://brailleauthority.org/tg/web-manual/ Accessed: 2024-09-03.

[8] Anke M. Brock, Philippe Truillet, Bernard Oriola, Delphine Picard, and Christophe Jouffrais. 2015. Interactivity Improves Usability of Geographic Maps for Visually Impaired People. *Human–Computer Interaction* 30, 2 (2015), 156–194. https://doi.org/10.1080/07370024.2014.924412

[9] Emeline Brulé and Gilles Bailly. 2021. "Beyond 3D Printers": Understanding Long-Term Digital Fabrication Practices for the Education of Visually Impaired or Blind Youth. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 44, 15 pages. https://doi.org/10.1145/3411764.3445403

[10] Gregory Clemenson, Antonella Maselli, Alexander Fiannaca, Amos Miller, and Mar Gonzalez-Franco. 2021. Rethinking GPS navigation: creating cognitive maps through auditory clues. *Scientific Reports* 11 (04 2021). https://doi.org/10.1038/s41598-021-87148-4

[11] P. Edman and American Foundation for the Blind. 1992. *Tactile Graphics*. American Foundation for the Blind. https://books.google.fr/books?id=C7vq4-Th71AC

[12] Christin Engel, Karin Müller, Angela Constantinescu, Claudia Loitsch, Vanessa Petrausch, Gerhard Weber, and Rainer Stiefelhagen. 2020. Travelling more independently: A Requirements Analysis for Accessible Journeys to Unknown Buildings for People with Visual Impairments. In *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility* (Virtual Event, Greece) *(ASSETS '20)*. Association for Computing Machinery, New York, NY, USA, Article 27, 11 pages. https://doi.org/10.1145/3373625.3417022

[13] M.A. Espinosa and E. Ochaíta. 1998. Using Tactile Maps to Improve the Practical Spatial Knowledge of Adults who are Blind. *Journal of Visual Impairment & Blindness* 92, 5 (1998), 338–345. https://doi.org/10.1177/0145482X9809200512

[14] D.L. Fazzi and J.M. Barlow. 2017. *Orientation and Mobility Techniques: A Guide for the Practitioner*. AFB Press, American Foundation for the Blind. https://books.google.fr/books?id=rIC-AQAACAAJ

[15] Franck Ganier, Charlotte Hoareau, and Frédéric Devillers. 2013. Évaluation des performances et de la charge de travail induits par l'apprentissage de procédures de maintenance en environnement virtuel. *Le travail humain* 76 (12 2013), 335–363. https://doi.org/10.3917/th.764.0335

[16] Nicholas A. Giudice, Benjamin A. Guenther, Nicholas A. Jensen, and Kaitlyn N. Haase. 2020. Cognitive Mapping Without Vision: Comparing Wayfinding Performance After Learning From Digital Touchscreen-Based Multimodal Maps vs. Embossed Tactile Overlays. *Frontiers in Human Neuroscience* 14 (2020). https://doi.org/10.3389/fnhum.2020.00087

[17] Nicholas A. Giudice, Hari Prasath Palani, Eric Brenner, and Kevin M. Kramer. 2012. Learning non-visual graphical information using a touch-based vibro-audio interface. In *Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility* (Boulder, Colorado, USA) *(ASSETS '12)*. Association for Computing Machinery, New York, NY, USA, 103–110. https://doi.org/10.1145/2384916.2384935

[18] Ed Griffin, Lorenzo Picinali, and Mark Scase. 2020. The effectiveness of an interactive audio-tactile map for the process of cognitive mapping and recall among people with visual impairments. *Brain and Behavior* 10 (05 2020). https://doi.org/10.1002/brb3.1650

[19] R.Dan Jacobson. 1998. Cognitive Mapping Without Sight: four preliminary studies of spatial learning. *Journal of Environmental Psychology* 18, 3 (1998), 289–305. https://doi.org/10.1006/jevp.1998.0098

[20] Albina Mościcka Jakub Wabiński and Guillaume Touya. 2022. Guidelines for Standardizing the Design of Tactile Maps: A Review of Research and Best Practice. *The Cartographic Journal* 59, 3 (2022), 239–258. https://doi.org/10.1080/00087041.2022.2097760

[21] Y. Jiang, M.-J. Lobo, S. Christophe, and C. Jouffrais. 2023. Semi-automated Pipeline to Produce Customizable Tactile Maps of Street Intersections for People with Visual Impairments. *AGILE: GIScience Series* 4 (2023), 29. https://doi.org/10.5194/agile-giss-4-29-2023

[22] Hernisa Kacorri, Sergio Mascetti, Andrea Gerino, Dragan Ahmetovic, Valeria Alampi, Hironobu Takagi, and Chieko Asakawa. 2018. Insights on Assistive Orientation and Mobility of People with Visual Impairment Based on Large-Scale Longitudinal Data. *ACM Trans. Access. Comput.* 11, 1, Article 5 (mar 2018), 28 pages. https://doi.org/10.1145/3178853

[23] J. Kalsron, J.-M. Favreau, and G. Touya. 2022. CrossroadsDescriber – Automatic Textual Description of OpenStreetMap Intersections. *AGILE: GIScience Series* 3 (2022), 40. https://doi.org/10.5194/agile-giss-3-40-2022

[24] Akif Khan and Shah Khusro. 2021. An insight into smartphone-based assistive solutions for visually impaired and blind people – issues, challenges and opportunities. *Universal Access in the Information Society* 19 (06 2021), 1–25. https://doi.org/10.1007/s10209-020-00733-8

[25] Shah Khusro, Babar Shah, Inayat Khan, and Sumayya Rahman. 2022. Haptic Feedback to Assist Blind People in Indoor Environment Using Vibration Patterns. *Sensors* 22, 1 (2022). https://doi.org/10.3390/s22010361

[26] Carine Lallemand. 2018. *Méthodes de Design UX. 30 méthodes fondamentales pour concevoir des expériences optimales. (2e edition).*

[27] Marvin Levine. 1982. You-Are-Here Maps: Psychological Considerations. *Environment and Behavior* 14, 2 (1982), 221–237. https://doi.org/10.1177/0013916584142006

[28] Kazunori Minatani, Tetsuya Watanabe, Toshimitsu Yamaguchi, Ken Watanabe, Joji Akiyama, Manabi Miyagi, and Susumu Oouchi. 2010. Tactile Map Automated Creation System to Enhance the Mobility of Blind Persons—Its Design Concept and Evaluation through Experiment. In *Computers Helping People with Special Needs*, Klaus Miesenberger, Joachim Klaus, Wolfgang Zagler, and Arthur Karshmer (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 534–540. https://doi.org/10.1007/978-3-642-14100-3_80

[29] Daniel R. Montello. 2010. You Are Where? The Function and Frustration of You-Are-Here (YAH) Maps. *Spatial Cognition & Computation* 10, 2-3 (2010), 94–104. https://doi.org/10.1080/13875860903585323

[30] Michael Neill. 2024. *Theory and Research Design Maps.* Taylor & Francis. https://www.taylorfrancis.com/chapters/edit/10.1201/9781482295375-27/theory-research-design-maps-michael-neill Accessed: 2024-09-03.

[31] Konstantinos Papadopoulos and Marialena Barouti. 2015. The Contribution of Audio-tactile Maps to Spatial Knowledge of Individuals with Visual Impairments. *Proceedings of ICEAPVI(International Conference on Enabling Access)* 01 (02 2015), 141–146.

[32] Kai-Florian Richter and Alexander Klippel. 2002. You-Are-Here Maps: Wayfinding Support as Location Based Service. (01 2002).

[33] M.C. Rodriguez-Sanchez, M.A. Moreno-Alvarez, E. Martin, S. Borromeo, and J.A. Hernandez-Tamames. 2014. Accessible smartphones for blind users: A case study for a wayfinding system. *Expert Systems with Applications* 41, 16 (2014), 7210–7222. https://doi.org/10.1016/j.eswa.2014.05.031

[34] Elen Sargsyan, Bernard Oriola, Marc J-M Macé, Marcos Serrano, and Christophe Jouffrais. 2023. 3D Printed Interactive Multi-Storey Model for People with Visual Impairments. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 540, 15 pages. https://doi.org/10.1145/3544548.3581304

[35] Falko Schmid, Colin Kuntzsch, Stephan Winter, Aisan Kazerani, and Benjamin Preisig. 2010. Situated local and global orientation in mobile you-are-here maps. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services* (Lisbon, Portugal) *(MobileHCI '10)*. Association for Computing Machinery, New York, NY, USA, 83–92. https://doi.org/10.1145/1851600.1851617

[36] Mark Blades Simon Ungar and Christopher Spencer. 1997. Strategies for Knowledge Acquisition from Cartographic Maps by Blind and Visually Impaired Adults. *The Cartographic Journal* 34, 2 (1997), 93–110. https://doi.org/10.1179/caj.1997.34.2.93

[37] Jing Su, Alyssa Rosenzweig, Ashvin Goel, Eyal de Lara, and Khai N. Truong. 2010. Timbremap: enabling the visually-impaired to use maps on touch-enabled devices. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services* (Lisbon, Portugal) *(MobileHCI '10)*. Association for Computing Machinery, New York, NY, USA, 17–26. https://doi.org/10.1145/1851600.1851606

[38] Jennifer Tennison, Spondita Goswami, Jesse Hairston, P. Drews, Derrick Smith, Nicholas Giudice, Andreas Stefik, and Jenna Gorlewicz. 2024. Bridging the Gap of Graphical Information Accessibility in Education With Multimodal Touchscreens Among Students With Blindness and Low Vision. *Journal of Visual Impairment & Blindness* 117 (01 2024), 453–466. https://doi.org/10.1177/0145482X231217496

[39] Simon Ungar. 2018. Cognitive mapping without visual experience. *Cognitive Mapping* (2018). https://api.semanticscholar.org/CorpusID:6094672

[40] W.R. Wiener, R.L. Welsh, and B.B. Blasch. 2010. *Foundations of Orientation and Mobility, 3rd Edition: Volume 2, Instructional Strategies and Practical Applications.* AFB Press. https://books.google.fr/books?id=hso50ocsEpsC

[41] Michele A. Williams, Caroline Galbraith, Shaun K. Kane, and Amy Hurst. 2014. "Just let the cane hit it": how the blind and sighted see navigation differently. In *Proceedings of the 16th International ACM SIGACCESS Conference on Computers & Accessibility* (Rochester, New York, USA) *(ASSETS '14)*. Association for Computing Machinery, New York, NY, USA, 217–224. https://doi.org/10.1145/2661334.2661380

[42] Michael Wong, Vishi Gnanakumaran, and Daniel Goldreich. 2011. Tactile Spatial Acuity Enhancement in Blindness: Evidence for Experience-Dependent Mechanisms. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 31 (05 2011), 7028–37. https://doi.org/10.1523/JNEUROSCI.6461-10.2011

[43] Georgios Yfantidis and Grigori Evreinov. 2006. Adaptive blind interaction technique for touchscreens. *Univers. Access Inf. Soc.* 4, 4 (may 2006), 328–337. https://doi.org/10.1007/s10209-004-0109-7

[44] Christophe Jouffrais Yuhao Jiang, María-Jesús Lobo and Sidonie Christophe. 2024. Producing accessible intersection maps for people with visual impairments: an initial evaluation of a semi-automated approach. *Cartography and Geographic Information Science* 0, 0 (2024), 1–21. https://doi.org/10.1080/15230406.2023.2295043

[45] Limin Zeng and Gerhard Weber. 2016. Exploration of Location-Aware You-Are-Here Maps on a Pin-Matrix Display. *IEEE Transactions on Human-Machine Systems* 46, 1 (2016), 88–100. https://doi.org/10.1109/THMS.2015.2477999

[46] Kaixing Zhao, Marcos Serrano, Bernard Oriola, and Christophe Jouffrais. 2020. VibHand: On-Hand Vibrotactile Interface Enhancing Non-Visual Exploration of Digital Graphics. *Proc. ACM Hum.-Comput. Interact.* 4, ISS, Article 207 (nov 2020), 19 pages. https://doi.org/10.1145/3427335

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