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► To cite this version:

Jérémy Albouys-Perrois, Jérémy Laviolle, Carine Briant, Anke Brock. Towards a multisensory augmented reality map for blind and low vision people: A participatory design approach. CHI 2018, Conference on Human Factors in Computing Systems, Apr 2018, Montréal, Canada. hal-01801116

HAL Id: hal-01801116

<https://enac.hal.science/hal-01801116>

Submitted on 28 May 2018

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Towards a Multisensory Augmented Reality Map for Blind and Low Vision People: a Participatory Design Approach

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ABSTRACT

Current low-tech Orientation & Mobility (O&M) tools for visually impaired people, e.g. tactile maps, possess limitations. Interactive accessible maps have been developed to overcome these. However, most of them are limited to exploration of existing maps, and have remained in laboratories. Using a participatory design approach, we have worked closely with 15 visually impaired students and 3 O&M instructors over 6 months. We iteratively designed and developed an augmented reality map destined at use in O&M classes in special education centers. This prototype combines projection, audio output and use of tactile tokens, and thus allows both map exploration and construction by low vision and blind people. Our user study demonstrated that all students were able to successfully use the prototype, and showed a high user satisfaction. A second phase with 22 international special education teachers allowed us to gain more qualitative insights. This work shows that augmented reality has potential for improving the access to education for visually impaired people.

ACM Classification Keywords

K.4.2 Social Issues: Assistive technologies for persons with disabilities; H.5.2 User Interfaces: User-centered design; H.5.1 Multimedia Information Systems: Artificial, augmented, and virtual realities

Author Keywords

Accessibility; visual impairment; geographic maps; augmented reality; participatory design

INTRODUCTION

Visually impaired people (VIP) face important challenges when navigating in unknown environments [1]. Orientation & Mobility (O&M) classes in special education centers teach VIP the skills required to navigate safely and autonomously in unknown environments. O&M instructors rely on different



Figure 1. A visually impaired student exploring the multisensory map. The system augments a tactile map with projection and audio output.

tactile tools, such as raised-line maps, small-scale models or magnet boards (see Fig. 2). These tools have proved to be efficient for spatial learning in the absence of vision, but possess limitations. For instance, once a tactile map is created, it is not possible to update its content. Accessible interactive maps have been developed to address these limitations [13]. Despite considerable progress, interactive maps developed to date, still have downsides. In this work we extend this progress by addressing two issues that are still encountered in many systems. First, most existing accessible interactive maps are limited to map exploration, and do not permit users to construct the maps themselves. Second, most existing interactive maps are research prototypes and only a few interactive maps have been studied and applied in real teaching environments [11]. Both issues are addressed in this project.

A participatory design approach [34] was applied to design the accessible interactive map. Over a period of 6 months we worked closely with 15 VIP (both blind and low vision), 3 O&M instructors and 4 other professionals from a local special



Figure 2. Tools used during O&M classes: (a) raised-line map, (b) small-scale model, (c) magnet board, (d) German film on rubber mat.

education center. Based on our observation of O&M classes and interviews, we developed a low-fidelity prototype which we improved in an iterative process. Then, we developed a high fidelity prototype based on the existing spatial augmented reality (SAR) toolkit PapARt [31] which was originally designed for sighted people. This toolkit combines a projector, a depth camera and a color camera and enables finger and object tracking (see Fig. 1). We combined this toolkit with tactile tools that are already used in O&M classes (see Fig. 2), and added audio output using a text-to-speech synthesis (TTS).

The prototype can be used in exploration mode and in construction mode. Exploration mode enables visually impaired students to explore existing raised-line maps (Fig. 1). Users explore the tactile map with both hands as they are accustomed to. Complementary visual information is projected on the raised-line map for the benefit of low vision students. Students can obtain an audio description by simply pointing to a tactile element with one finger and pressing a key on the keyboard. Construction mode enables visually impaired users to construct maps or itineraries themselves by combining magnet boards with audio output and projection (Fig. 7). Our prototype follows a step-by-step learning scenario to provide instructions to the students, and prompts them to place points of interest (POIs) or road elements on the map. The user may verify whether an element is placed correctly using the same interaction as in exploration mode (pointing and pressing a key). If the element is not in the right place according to the scenario, then the system provides corrective directions.

In an evaluation with 8 visually impaired students we demonstrated experimentally that all students (regardless of visual abilities and gender) were able to successfully use the prototype. Standardized questionnaires showed a high satisfaction and users were enthusiastic about the interactive map prototype. The results from the user study also allowed us to further improve the prototype. In an international workshop, we obtained qualitative feedback from 22 special education teachers and O&M instructors (of whom 3 were visually impaired). Overall, participants found the system useful and thought that it would make lectures more fun and engaging.

To sum up, there are two main contributions of this paper:

1) Technical Contribution: The design and implementation of an accessible SAR map combining visual feedback with audio output and tactile cues. This prototype extends the current state of the art on accessible interactive maps by pro-

viding the possibilities to both explore and construct maps. 2) Methodological Contribution: The use of a participatory design approach (observation, ideation, low-fidelity prototyping, evaluation) involving 15 visually impaired students and 3 O&M instructors over a period of 6 months, as well as an international workshop with 22 special education teachers and O&M instructors. This approach provides strong guarantees of usefulness and accessibility of the developed prototype.

RELATED WORK

This paper draws motivation from three research streams in the literature: participatory design with VIP, accessible interactive maps for VIP and spatial augmented reality.

Participatory Design with People with Visual Impairments

Participatory design is well-documented in HCI. Target users participate directly and proactively in the design process [42] which is iterative and often structured in several phases: establishing an understanding, generation of ideas, prototyping and evaluation [34]. Researchers and practitioners use a variety of methods with different degrees of participation that they adapt to each problem [20], such as observation, brainstorming, technological probes, and iterative prototyping.

Phillips and Zhao [36] showed that users with special needs most frequently abandon technological aids if their opinions were not considered during the design process. It is therefore crucial to empower impaired users to contribute to the design of assistive technology [54]. However, typical methods used to engage users in the design process are based on the visual sense (e.g. paper prototyping), consequently excluding visually impaired users [34]. Several researchers and practitioners addresses this issue. Henry [21] provided practical recommendations to include people with diverse impairments in the design process. For understanding users' needs, Shinohara et al. [49] and Rector et al. [41] used interviews and observational studies, whereas Metatla et al. suggested using focus groups and technology demonstrations [34]. Bennett et al. [5] proposed ideation workshops with people having various impairments and identified challenges, for instance related to communication and visualization of ideas. For iterative prototyping with VIP, Tanhua-Piiroinen and Raisamo [53] proposed using tangible models (e.g. plastic models and cardboard mockups) and haptic interfaces, and Miao et al. [35] proposed tactile paper prototypes. Ramloll et al. [39]

used low-fidelity prototypes, while Metatla et al. [34] provided highly malleable implementations of early prototypes that could be adapted to users' wishes and ideas in real time. In the practical context of the home, Branham and Kane [8] observed that accessibility is already co-constructed between VIP and sighted partners. To sum up, a variety of methods can be applied when designing with and for VIP.

Accessible Interactive Maps for Visually Impaired People

In the past decades, several researchers have developed interactive maps for VIP [13]. Some prototypes use a camera and image recognition algorithms to detect touch on raised-line maps [16, 45, 51], digital maps [28], regular visual paper documents [24], 3D printed maps [18] or tangible objects and tactile grids [43]. Beyond maps, camera-based finger tracking has been used for tangible newspapers [50], and to obtain audio descriptions for 3D printed graphics [47, 48]. These works suggest that camera-based finger tracking can be successfully used in technology for VIP.

Interactive tactile maps are more efficient and satisfactory than raised-line maps with braille [9], and are beneficial for spatial learning [17]. Despite this, interactive maps developed to date, still have downsides. First, most existing interactive maps are research projects and remain in the laboratory. Only a few prototypes have been studied and applied in real teaching environments [11, 17]. Second, most maps are limited to map exploration and only few prototypes permit users to construct the maps themselves. Allowing a visually impaired student to construct a map has however two advantages: first it allows teachers to verify that the mental representation of the student is correct, and second externalizing a mental map fosters a better memorization of the spatial information [27]. As examples of systems that allow map construction, Schneider and Strothotte [43] designed a prototype for the construction of itineraries with building blocks of various lengths. This device has been limited to route construction, and has not been formally evaluated. The Tangible Pathfinder [46] allowed visually impaired users to construct a map with small objects representing pavements, sidewalks, etc. and audio instructions. To our knowledge its usability has not been evaluated. In the Tangible Reels system [14], 3D tangible objects with retractable reels were used to build a map with POIs and routes, combined with audio feedback. Tangible Reels proved to be efficient for map construction, easy to move and stable, and allowed participants to build a mental map. Yet, the height of the objects and manipulation of the reels was difficult for some users. Beyond maps, McGookin et al. [33] designed a tangible system with audio feedback allowing VIP to construct graph and chart-based data. To sum up, interactive maps for VIP exist, but are rarely designed for in-situ teaching environments, and mostly limited to map exploration (and not construction of maps). Both issues are addressed in this project.

Spatial Augmented Reality Toolkits

Augmented Reality (AR) systems are interactive systems which combine real and virtual objects in a real environment, run in real time and align virtual and physical objects with each other [3]. More specifically, Spatial Augmented Reality (SAR) systems have taken AR beyond traditional eye-worn

or hand-held displays by augmenting the user's environment, e.g. through projection [7]. Since the Digital Desk [56], many SAR systems have been designed with the purpose to extend the desktop surface, e.g. for computing in MagicDesk [6] or for remote collaboration in Illumishare [23]. These systems have been equipped with depth cameras to ease object and finger detection and tracking.

As such systems become more complex, application toolkits are developed to handle the calibration of cameras and projectors, object and finger tracking and the creation of applications in SAR. Most of the toolkits originated as research projects. A noticeable one is Microsoft RoomAliveToolkit [22] which enables large scale multi-device tracking and projection. This toolkit handles calibration and projection from the ground up. Currently, the prototyping of SAR applications is quite long, and moving SAR applications to different environments requires additional work. The WorldKit toolkit [57] has not been released for public testing. While promising, the focus was on the creation of custom interfaces in SAR in the environment. Lampix [29] works on small-scale SAR and released a framework to test the SAR software (but not yet the hardware).

Most people imagine AR prototypes as visual systems. However, AR does not necessarily apply to the visual sense only, but potentially to all senses, including hearing, touch, and smell [3]. Yet, while there is a large body of work on AR for sighted people, there are only very few works on such systems for VIP. As an example, Zhao et al. recently investigated the use of commercial optical see-through AR glasses [58] and Head-Mounted Displays [59, 60] for low vision users (but not blind people). Profita et al. [38] observed a higher social acceptability of head-mounted displays if the device was being used to support a person with a disability. We are not aware of any SAR systems for VIP. In this paper we present the extension of a SAR toolkit for low vision and blind people by combining visual, auditory and tactile modalities.

METHOD AND PARTICIPANTS

The work presented in this paper is part of an international research project with the goal to improve spatial learning for visually impaired children. Spatial learning is important not only to support wayfinding and navigation, but is also considered as one of the key skills for STEM subjects (science, technology, engineering and mathematics). More concretely, the goal of the project presented in this paper was to adapt an existing augmented reality toolkit so it could be used as a spatial learning tool in a special education center for VIP. While the available hardware as well as the objective were well defined from the beginning, the way this tool should be designed was not. In order to reply to the needs of VIP and their teachers, we applied a participatory design approach [42].

Our project consisted of two phases (see Fig. 3). Phase 1 comprised a participatory design phase with 15 VIP, 3 O&M instructors and 4 professionals from a local special education center over a period of 6 months. Phase 1 started with observation of O&M classes, and interviews with instructors and students (as proposed in [49]). On this basis, we developed a low-fidelity prototype and then entered into an iterative process of prototype use and prototype improvement. At the end

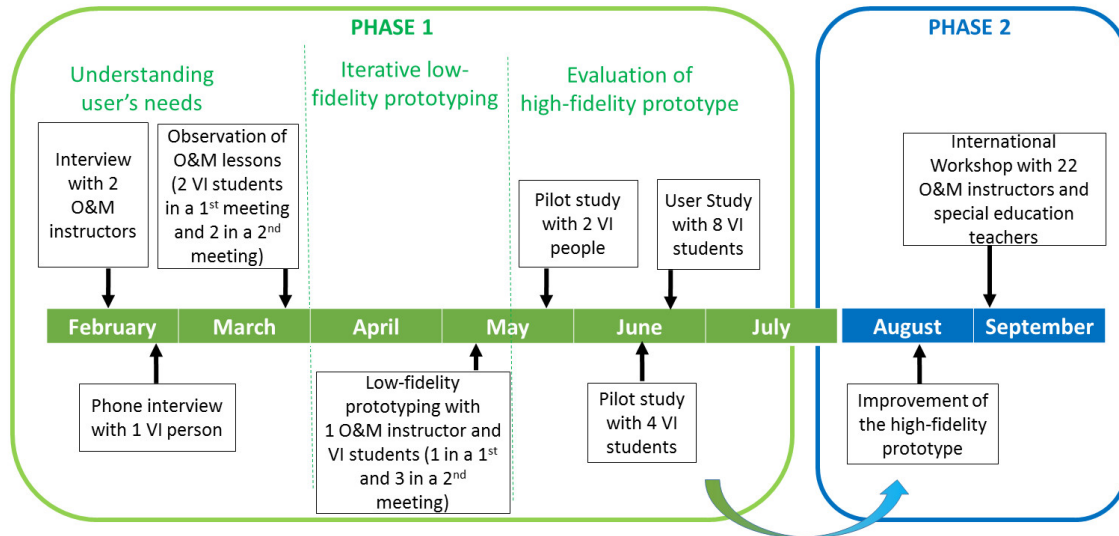


Figure 3. Schedule of the different steps of the participatory design approach. Phase 1 (green): collaboration with a local special education center, Phase 2 (blue): collaboration within an international project.

of these iterations, we developed a high fidelity prototype, which was then evaluated using an experimental protocol with 8 visually impaired students. Phase 2 comprised an international workshop with 22 teachers and O&M instructors, in which we collected qualitative feedback.

A summary of our visually impaired participants of Phase 1 can be found in Table 1. We collaborated with IRSA, the Institute for Deaf and Blind People in New Aquitaine region in France. We also recruited participants through the local university support service PHASE from the university of Bordeaux and our personal network. Our participants had a wide range of visual impairments, from low vision to blindness. Most studies focus on blind people who form a more homogeneous

group to be studied. Therefore, there is little knowledge about assistive technology for people with low vision [52]. Two participants had cognitive impairments in addition to the visual impairment. Only few studies included people with multiple impairments [11] as it is difficult to do a controlled user study with them. However, we believe that it is important to include people with low vision and people with multiple impairments in the design and evaluation of assistive technology, as special education schools need to have solutions to teach these children. All participants of Phase 1 received a gift check for their participation. Participants signed a consent form, and parents signed for minors. The protocol and the consent form were approved by the ethics committee of our institution. Our participatory design approach also included professionals from the special education center. Three O&M instructors were closely involved in the participatory design process. Four other professionals assisted the user study as observers and provided qualitative feedback about their impressions: one orthoptist, two tactile transcribers, and one technical advisor.

MATERIAL: THE AUGMENTED REALITY TOOLKIT

We used the SAR Toolkit PapARt (Paper Augmented Reality Toolkit) ¹ to develop our prototypes. PapARt was initially made to assist the creation of physical drawings or paintings for sighted people [31]. It relies on open source components: ArtoolkitPlus [55] for tracking, ProCamCalib [2] for projector and camera calibration, and Processing [40] for developing applications. Like RoomAlive [22], it proposes full calibration for projector, color camera and depth camera. Its focus is on prototyping applications for tabletop SAR with a dedicated pre-calibrated hardware. PapARt uses a short throw projector, a depth camera, and a color camera which are pre-calibrated and integrated inside a dedicated hardware as show in Fig. 4. The software is implemented as a Processing library that

Id	Gender	Age	Description
VI1	M	20	Early-blind, no light perception
VI2	M	18	Low vision
VI3	M	16	Early-blind, with light perception
VI4	F	17	Low vision from birth
VI5	M	17	Early-blind, with light perception
VI6	F	11	Low vision from birth
VI7	M	40	Early-Blind with light perception
P1	F	17	Early-blind, with light perception
P2	F	18	Low vision from age 13
P3	F	16	Low vision from age 14
P4	F	21	Low vision (age unknown)
P5	M	16	Low vision (age unknown)
P6	M	15	Blind from age 5
P7	M	14	Low vision from birth
P8	M	15	Low vision from birth

Table 1. Visually impaired people participating in Phase 1 of our participatory design approach. VI1 to VI6 = participants in pilot study, VI7 phone interview, P = participants in user study

¹<https://github.com/poqudrof/Papart>



Figure 4. PapART hardware (a) first and (b) second version.

abstracts hardware and enables the creation of "paper touch screens". The system tracks visual markers on paper sheets and projects on the sheet. Using the depth camera, the system detects fingers and objects alike and tracks them over time on and above (5mm) the surface. PapART is distributed under LGPL. The project is actively maintained and extended by Inria and RealityTech.

Two hardware versions were used in this project (Fig. 4). The first one was equipped with an ASUS B1MR short throw 720p projector, a Kinect for Xbox 360, and a Playstation Eye camera. The computer was an Intel NUC with a core i5 and 8Gb of RAM. The second hardware used an ASUS P3B short throw 720p projector, and an Intel Realsense SR300 (combining depth and color camera). The computer was custom built with an Intel core i3 CPU and 8 Gb of RAM. The second version was easier to transport, as it was more light weight than the first one and it could be disassembled into several pieces.

PHASE 1

As shown in Fig. 3, we met O&M trainers and VI students repeatedly during Phase 1 of our participatory design approach.

Observation and Interviews

The first step of participatory design is to create an understanding of users' needs [34]. Our goal was to understand how an O&M class is conducted and to observe the different tools that are used. To do this, we organized four meetings. First, we interviewed two O&M instructors. Meeting 2 was a phone interview with a VIP who had followed O&M classes as a child (VI7). During meeting 3 and 4, we assisted O&M classes and interviewed the students (P1, P2, P3 and VI5).

We learned that in a first O&M class at IRSA, instructors and visually impaired students explore an outdoor or indoor environment together. Then, in the next session in the classroom they reconstruct or draw this environment using mainly two tools (Fig. 2). Magnet boards can be used to construct a map with magnets of fixed size. This allows to build complex spatial configurations (e.g., road crossings). The second tool is drawing on German film (transparent sheets) over rubber mats. The drawing leaves a tactile trace on the sheet which can be detected by VIP through manual exploration. Two main tools are used for exploration of existing maps: tactile maps and small-scale models (Fig. 2). One downside of both is that

once produced the content cannot be modified. No electronic tools, such as interactive maps, are employed at IRSA. When discussing with the visually impaired students we learned that they had a personal preference for certain tools. P3, for example, appreciates using magnets to construct, but also to explore an existing raised-line map. P2 on the other hand does not like tactile braille maps.

In the fourth meeting (VI5 and P1) we also presented different tactile elements like magnets combined with foam paper, modeling clay and pipe cleaners. The students liked modeling clay and magnets. They suggested to use magnets for representing POIs (e.g. buildings, house blocks), and modeling clay for roads or tramway rails. We also asked which TTS they use in their daily lives, e.g. as part of their screen reader, and the different options they change. We learned that it was important for them to change speed and volume of the TTS. Most students would prefer if our system used the same TTS as their screen readers (Jaws and VoiceOver). Unfortunately, high quality non-English voices are costly.

Based on these observations and interviews we identified the following needs for a tool to be used in O&M classes:

- 1) An exploration mode is needed so that VIP can explore a readily existing map.
- 2) A construction mode is needed to support construction activities in O&M classes, which improve spatial learning [27]. This mode must enable the students to construct a map step by step and provide instructions and corrections. O&M instructors did not want to be entirely replaced by the system, but requested a tool which would support their work.
- 3) The context of special education centers makes it crucial to design a system that can easily be controlled and manipulated by teachers. Thus, we decided to augment existing material (e.g., magnet boards, tactile maps) rather than to design different tools (such as in [14]).

Ideation and Low-fidelity Testing

In a second step, we implemented a low fidelity prototype using magnets and modeling clay as tokens and MaryTTS as a free TTS which provides support for several languages [44]. We used this prototype as design probe (as in [34]) for choosing tactile and audio cues for our high-fidelity prototype. The prototype was tested in a session with one O&M instructor and one student (VI5), and a session with one O&M instructor and three students (P1, P2, P3). We pre-constructed a map



Figure 5. Wikki Stix and magnets with foam paper on a magnet board.

with modeling clay and magnets. The students could explore this map and get audio feedback regarding the different tactile elements. The second part of the test was the construction of a simple map with five elements by the students. Parts of the system were simulated using the Wizard of Oz method [26].

This step allowed us to identify important issues. First, even if in the prior meetings students had suggested using modeling clay, it turned out to be too difficult to use for non-visual construction. Moreover, some students told us that they did not appreciate the texture of pipe cleaners. After discussing with the instructors we decided to use Wikki Stix (<https://www.wikki-stix.com/>), woolen strings covered with colourful wax (see 5). Another solution has been proposed in [14] in the form of retractable reels. However, the manipulation of the reels has proved to be difficult for VIP and "modifier elements" were needed in order to bend the lines. Wikki Stix on the other hand are easy to bend, stick to any surface but are removable, and are already regularly used during O&M classes at IRSA. We also discussed about 3D printing objects (e.g. houses, as in [11]) instead of using flat magnets with foam paper. Yet, most participants preferred the idea of flat objects. Prior research has also demonstrated that 3D tangible elements are difficult to use by VIP as they knock them over while exploring graphics or maps [33]. Therefore, we decided to stick to flat magnets.

Furthermore, we discussed how to provide feedback for map elements. Most VIP use both hands to explore maps and thus many fingers touch the map at the same time [19]. Prior studies showed that VIP do not appreciate to receive audio feedback for all elements that they touch on a tactile map or graphic [9]. Thus, we suggested to use a speech recognition system to request audio feedback (i.e. VIP would pronounce a keyword while touching the map). However, due to prior bad experiences with the speech recognition systems in their smart phones, all visually impaired students were worried about the quality of speech recognition systems. Therefore, we proposed to use a key press (i.e. VIP press a key or button with one hand while touching the map with the other hand). Moreover, we decided to use a different TTS as all four VIP stated that the intelligibility of the voice was poor and that they did not like it. As mentioned above, they were all accustomed to high quality voices from their screen readers. We used PicoTTS (<https://svoxmobilevoices.wordpress.com/>), a free TTS that provides multiple languages and had been used in one of the first TalkBack screen readers in Android phones.

High-fidelity Prototype

The design of a high-fidelity prototype was based on previous iterations. The original version of the PapARt toolkit foresaw only visual feedback. We decided to maintain visual feedback as we suspected it to be beneficial for low vision users, even though it was not specifically designed for them. As stated above, we used PicoTTS and existing tactile tools (raised-line maps, magnet boards, Wikki Stix).

A PNG image served as the visual base of the map. A vector graphic file (SVG) containing the digital information of the map, e.g. the positions of the different elements and their textual description, was then drawn on the base of this PNG using inkscape. The prototype was calibrated to the position

of the projected image. Interaction between users and the map was based on the system's finger tracking algorithm: the system retrieved the position of the finger on the map and compared it to the map information contained in the SVG file in order to provide the correct audio output. As the system has multitouch capacities, users were asked to point with one single finger in order to have one unique touch point when they requested audio output. They could explore the map with both hands, as they are accustomed to [19], when they did not request any audio information.

The PapARt framework allows to project a virtual button interface, but it is impossible for VIP to interact with buttons they cannot feel. Therefore we enabled interaction by pressing on specific keys on a keyboard which we marked with foam paper. Another challenge was to represent the interactive zone for the VIP, i.e. the area in which touch interaction is possible. Our prototype projects the interactive zone on a flat surface. The absence of physical limitations of a device, makes it impossible for VIP to perceive a haptic reference frame [13]. Thus, we decided to add a physical frame (Fig. 6). This frame was laser cut from a transparent plastic sheet.

Finally, we implemented two different modes: exploration and construction modes. In exploration mode, our prototype enables visually impaired students to explore existing maps by combining raised-line maps with audio output and projection. Users explore the tactile map with both hands as they are accustomed to [19]. Complementary visual information is projected on the raised-line map, for the benefit of low vision students. Students can obtain an audio description by simply pointing to a tactile element with one finger and pressing a key on the keyboard. In construction mode, our prototype enables visually impaired users to construct maps or itineraries themselves by combining magnet boards with audio output and projection. O&M instructors developed a step-by-step learning scenario (see supplementary material), and our augmented reality prototype follows this scenario to provide instruction to the students. Starting from elements placed by the teacher, the system prompts the student to place a point of interest or a road on the map in relation to these starting elements. The student then places elements on the map: magnets with foam paper for POIs, and Wikki Stix for road elements. For POIs, the user may verify whether an element is placed correctly

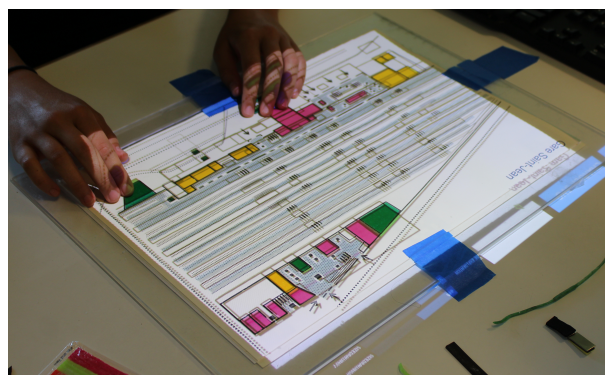


Figure 6. Student using our prototype during exploration mode: tactile map combined with projection and audio output.



Figure 7. Construction Mode: building a map using Wikki Stix and magnets combined with projection and audio feedback.

using the same interaction as in exploration mode, that is by pointing to an element and pressing a key to hear an audio description. If the element is not in the right place according to the scenario, then the system provides corrective directions (left/right/top/down, similar as in [25]). For line elements, the "verification mode" was more challenging to design, and to our knowledge no prior study has investigated this. We designed an interaction technique, in which the student points to the start position of the line with one finger and then presses and holds the key. He or she then follows the line by sliding the finger along the Wikki Stix. As long as the line is correctly placed, a beep sound is played. When the finger touches a portion of the line which is incorrectly placed, the system verbally provides directions to help the student correct his construction (as for POIs). We designed this interaction technique, as it allows users to identify which parts of the line are correctly placed and to modify only the incorrect parts.

PHASE 1: USABILITY STUDY

The aim of this user study was to evaluate the usability of the developed prototype both for low vision and blind people in the context of O&M classes at school. We also wanted to gain feedback from professionals involved in this study. We used the apparatus described above.

Participants

Table 1 provides details about the participants in our study (age, gender and visual abilities). VI1 to VI6 participated in the pilot study: VI1 and VI2 were university students, and VI3 to VI6 were students at the special education center. P1 to P8 participated in the user study. They were all students at the special education center. P4 and P7 are attained with additional cognitive impairments. Today many students with visual impairment are integrated into main stream schools, and special education centers mainly care for students with multiple impairments [11]. Due to constraints from the school, we were not able to "select" participants. Consequently, the number of low vision (6) and blind people (2) was not equal. We were however able to conduct the experiment with an equal number of women (4) and men (4).

Experimental Design

In order to avoid bias, the order of presentation of exploration and construction modes was counterbalanced. For the exploration mode we used a raised-line map showing the local train station (Fig. 6). This map has been drawn and printed on swell-paper by a transcriber in the special education center. The train station scenario was chosen as it is interesting for the students in their real life. The station has recently been renovated and its new layout was therefore unknown to the participants. As can be seen in Fig. 6 the layout of the train station is quite complex, showing for instance train tracks, a tramway stop, shops and services (e.g. service for travellers with special needs, ticket store). For the construction mode, we used a step-by-step learning scenario written by the O&M instructors (see supplementary material). This scenario corresponded to the itinerary from a central square to the public garden. It involved using the tram and walking. Participants were told that they had to guide "loco" on her itinerary to find her friend "motion" in the public gardens.

Usability was evaluated by measuring efficiency, effectiveness and satisfaction. Efficiency was measured for the exploration mode as the time that users took to reply to the questionnaire, and for the construction mode as the time needed to perform the whole learning scenario. Effectiveness for the exploration mode was measured as the number of errors when replying to spatial questions, and for the construction mode as the number of mistakes (misplacement of objects) and number of repetitions of instructions. Satisfaction was measured across both modes by using SUS [10] and UEQ [30].

Instructions

The study consisted in a familiarization phase followed by construction and exploration tasks in counterbalanced order. During familiarization, we used a third map for both modes. This map showed an important public transport station where several tramway lines intersect. During familiarization with the exploration mode, participants were told how to explore an existing map and to obtain audio output. For the construction mode, participants had to reconstruct a small map, in order to learn how to correct the position of objects and lines. Participants could practice as long as they wanted.

Participants either started with exploration or construction mode. In the exploration mode, participants were allowed to freely explore the map of the train station for ten minutes. Then, they were asked 12 questions about the map while they were allowed to explore the map (4 questions about the general structure of the train station, 4 questions about the shops, and 4 questions about the services). The purpose of this step was to force all participants to explore the entire map. It also allowed us to verify that participants were able to acquire information about all map elements. Then, we removed the map and participants had to answer by heart to a series of 12 questions about the spatial layout of the maps (3 general questions about the train station, 3 questions about location estimation, 3 questions about direction estimation, 3 questions about distance estimation). The series of questions was based on prior similar studies [9, 17, 37] and recommendations by Kitchin and Jacobson [27]. As suggested by Giraud et al. [17]

we provided 4 multiple choice replies for each question, thus reducing the chance level to 25%.

In the construction mode, one O&M instructor read the learning scenario to the participants. The scenario contained questions which allowed her to evaluate the knowledge of each student and to react to each student's needs (e.g. provide explanations about the cardinal system if unknown to the student). This corresponded to the way how the O&M instructor normally conducted her classes. Our prototype then announced instructions that the students had to follow (e.g. "between the tram stop and the public garden there is triangular block of houses. Place the block of houses on the map."). After placing map elements, the students were invited to verify their position and correct them if necessary. Students could repeat instructions if necessary. We logged the number of misplacements and the number of repetitions they requested.

After having done both exploration and construction, participants were asked to reply to SUS [10] and UEQ [30] questionnaires. We also asked them for qualitative feedback. In some sessions, professionals from the special education center (e.g. tactile transcribers) participated as observers. They were invited to reply to a questionnaire and provide qualitative feedback and ideas on how to improve the prototype.

Pilot Study

A Pilot Study was conducted with six visually impaired students (two university students VI1 and VI2, and four students from the special education center VI3, VI4, VI5 and VI6). The Pilot study followed the same experimental protocol as the usability study. The observations from the pilot study allowed us to make improvements to the prototype (e.g., precision of finger detection). We also changed some questions in the spatial questionnaire which appeared to be ambiguous.

Experimental Study Results

Efficiency

In exploration mode, all participants explored the map during 10 minutes. Then, participants replied to a series of questions while still accessing the map, and a second questionnaire without access to the map. We measured the time each student took to answer the series of questions with and without access to the map. Each questionnaire was composed of 12 questions. The time without access to the map was lower (mean 7.25 min; SD 4.31) than with access to the map (mean 8.5 min, SD 2.92). This is not surprising as in the latter case, the exploration of the maps required some time. However, the difference is rather small. Moreover, most participants answered all questions in less than 20 minutes, i.e. less than 1 minute per question. This shows that VIP can efficiently acquire spatial information with the map prototype.

In construction mode, we measured the total time required to complete the learning scenario. The mean time was 24.11 minutes (SD = 7.27, min = 14.49, max = 33.72). This time includes the interaction between the student and the instructor. We noticed that there was quite a high difference between the mean times for the different steps of the scenario. For example, the mean time for step 4 is 6.93 minutes, whereas for step 2 it is 1.05 minutes. In step 2, which was quite simple, the

student had to place a magnet to represent a tram stop. Step 4 took more time because besides placing map elements, the instructors also asked the student questions about their journey. For example "What do you do before crossing a road?". We investigated whether the order of tasks had a significant effect on the time for the construction mode (our hypothesis was that construction mode would be easier to use, if exploration mode has been done beforehand). Data were normally distributed (Shapiro-Wilk; $W = 0.93$; $p = 0.48$). A t-Test did not show any significant difference between both groups ($t(6) = 0.56$, $p=0.6$). Beginning with exploration mode did not speed up the use of construction mode.

Effectiveness

In exploration mode, effectiveness was measured as the number of correct replies to the questionnaires about map content and configuration, as a main purpose of maps is to enable people to acquire and memorize spatial information. On average, students made more error without the map (mean 3.8; SD 1.81) than with the map (mean 2.25; SD 1.16). This is not surprising as access to the map allows students to obtain the required information. Despite this, we measured some mistakes even with access to the map. For example, one question assessed the total number of restrooms in the train station. Several participants stopped searching after they found the first one, without exploring the rest of the map. In many prior studies men perform better than women in spatial cognition tasks [32]. Therefore, we compared the number of errors between both groups for the questionnaire without access to the map. Errors were not normally distributed (Shapiro-Wilk; $W = 0.02$; $p = 0.04$). There was not statistical difference between both groups (Mann-Whitney test, $U = 7$, $p = 0.77$).

We used two measures for the effectiveness of the construction mode : the number of times participants listened to each instruction and the number of errors for each step (i.e. misplacing tactile elements and correcting their position). On average each student listened to the instructions two times (one is the minimum, SD 0.52). This suggests that most students were able to easily understand the instructions. Moreover, the number of errors when constructing the map was low. Students made on average 5.1 errors for the entire construction mode (SD 2.32). This represents a mean error of 1.02 for each step of the scenario, suggesting that students were able to construct the map with a reasonable amount of corrections. Again, we investigated if there was a significant difference regarding the number of errors between the groups which started with exploration or construction respectively. Data were normally distributed (Shapiro-Wilk; $W = 0.97$; $p = 0.88$). We did not observe any significant difference between both groups (t -Test, $t(6) = 0.0$, $p=1$) and the mean error was identical (5.19).

User Satisfaction

Satisfaction was measured with the standardized SUS [10] and UEQ [30] questionnaires. The results from the SUS are shown in Fig. 8. Bangor et al. [4] proposed a scale to assign attributes to SUS scores. All participants except P1, P4 and P7 ranged the prototype above "good" usability. The UEQ provides 6 measures: attractiveness, perspicuity, efficiency, dependability, stimulation and novelty. Results are "excellent"

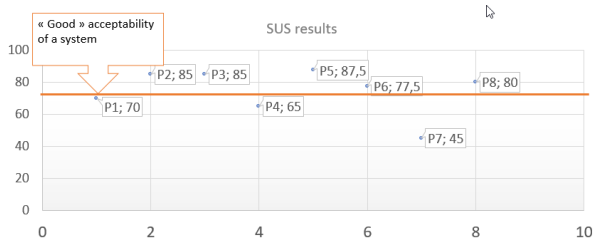


Figure 8. Results of the SUS questionnaire [10] for each participant. The orange bar marks the "good" usability value from Bangor et al. [4].

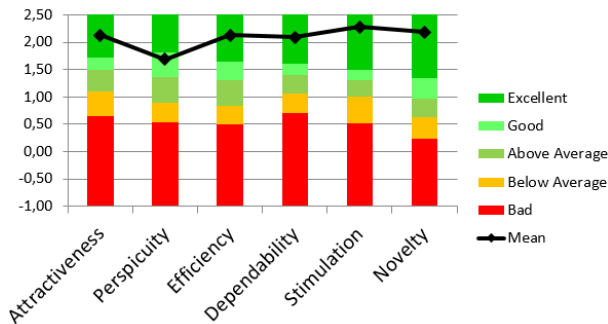


Figure 9. Results of the UEQ questionnaire [30] per category.

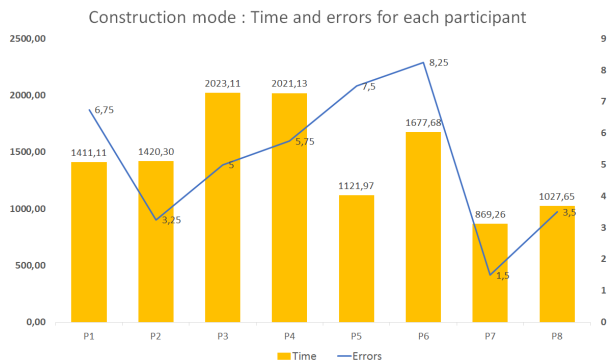


Figure 10. Construction mode mean time in minutes (yellow bars) and number of errors (blue line) for participants P1 (left) to P8 (right).

for all measures, except for the "Perspicuity" which is "good" (Fig. 9). The problem for this item may be the quality of our TTS, as the participants reported issues with it.

We also gathered qualitative feedback. Participants were generally enthusiastic about the prototype. One participant did not want to stop "playing". 7 out of 8 students appreciated the audio feedback. This is coherent with prior studies demonstrating that especially younger VIP preferred audio output over braille text [9]. 5 students liked the construction mode of our prototype and especially the possibility to be corrected by the system. They felt that the system would judge them less than a human being. 6 participants wanted to use this prototype during their classes, but did not want to use it without the help of an O&M instructor, especially in construction mode. This matches the design of the prototype which was done for collaborative use with an O&M instructor. Interestingly, some of the less autonomous participants stated that they felt capable

of using the prototype on their own. This suggests that these participants found the use of our map prototype easier than the use of other tools.

On the other hand, all participants criticized the precision of the finger detection. Indeed, the way how participants bent and held their finger impacted the precision. Furthermore, users still did not appreciate the TTS. This was surprising to us, as we had chosen a TTS which has also been used in early TalkBack screen readers of Android phones. We identified these two points as main features that needed improvements for a future version of the prototype.

Inter-individual differences

VIP present a heterogeneous group with a variety of inter-individual differences, such as age at onset and duration of visual impairment, etiology, mobility skills, braille reading skills and use of assistive technology [12]. Indeed, we observed large discrepancies among participants (see Fig. 10). Legally blind participants (P1 and P6) were not the ones who required the most time, however they were among the ones with the most errors. P7, a low-vision student, was quickest and made the smallest number of errors. However, as shown above, his SUS score also was lowest. When evaluating the UEQ we identified P7 as a person who gave incoherent replies (2 incoherent replies marked as critical by the UEQ questionnaire evaluation tool). O&M instructors were generally able to predict which students would have more problems with the tasks than others. All people with residual vision made use of the projected information, even those who were legally blind and trained to manual map exploration. Prior studies made similar observations [52]. In our study, one person with low vision was photosensitive and the projection was hurting him. Our system allows to switch projection on and off. We suggest foreseeing this possibility in Assistive Technology to allow users to adapt technology to their personal needs.

Qualitative replies and suggestions from Observers

Some professionals from the special education center participated as observers in the user study (one orthoptist, two tactile transcribers, and one technical advisor). They wanted to see how the students interacted with our prototype. Observers did not interfere during the session. Afterwards, we sent them a questionnaire and 3 observers provided qualitative replies and suggestions. Observers generally liked the prototype, a technology that they had never experienced before. They found this tool more attractive and useful than a simple tactile map and braille legend. The observers also provided some ideas for future work. For example, they suggested to extend the scope beyond geographic maps in order to help the children with other subjects, such as mathematics.

PHASE 2: INTERNATIONAL WORKSHOP

Improvements and changes to the prototype

As presented in Fig. 3, our project consisted of two phases. The results from the User Study in Phase 1 allowed us to improve the prototype. Notably, we were able to further increase the precision of the finger detection by providing a virtual slider that allows to adapt the finger detection threshold to

each user's individual way of pointing (e.g., different angles of inclination). Moreover, we changed from hardware version 1 to 2 which was easier to travel with. Besides, we translated the audio output to English. In the first version of the prototype, users had to press a key on a keyboard marked with foam paper to obtain audio feedback. To make it easier to press the right key, we designed a 3D printed box with one button for accessing the next information, and one for repeating the last instruction. We also foresaw two potentiometers to later add the possibility to speed up or slow down the speed of the TTS, as suggested by participants of the ideation phase.

Workshop Outcomes

We presented our prototype during an international workshop to 22 people: teachers, O&M instructors and technicians from two schools for the young blind in Romania and Greece, and teachers from a teacher training institute in Romania. Three of the teachers were visually impaired. We focused on qualitative feedback. Participants found the system useful and thought that it would make lectures more fun and engaging. They would prefer to include the application in a smart board, as the rooms of their school are already equipped with it. Indeed, they were worried about the costs for acquiring an augmented reality prototype. In line with the professionals in Phase 1, some participants suggested to use the prototype in contexts that go beyond geography, such as studying schematic diagrams of flowers. One participant suggested to provide only names in a first use of the prototype, and then to increase the amount of information at each session. Regarding the construction mode, participants agreed that a teacher was needed to help execute it. Also, they suggested to provide progressive correction (similar as in [14]). One person suggested to include automatic route calculation (e.g., from Google maps). Another person proposed a device that can be used indoors in O&M classes, but also taken outdoors during navigation (as suggested also in [46]).

DESIGN GUIDELINES

From our study we derive the following design guidelines: 1) The design of interactive maps for VIP should go beyond map exploration to also allow map construction. We present a novel prototype which allows to do so by using spatial augmented reality. 2) More work should be done on the use of augmented reality and tangible interaction by VIP. These technologies allow a greater flexibility than static devices. Researchers interested in audio-haptic interfaces can adapt existing AR toolkits to VIP by adding audio and tactile cues, if these cues are designed according to users' needs and preferences. 3) When designing educational technologies for people with special needs, it is important to include the target population as well as stakeholders in the design process. Implying the first is crucial for making the technology accessible, implying the latter for the technology to be adopted in the classroom.

DISCUSSION

We developed a multisensory map based on an existing augmented reality toolkit originally designed for sighted people. We applied a participatory design approach, as it is crucial to involve people with impairments in the design of assistive

technology. VIP involved in our project had diverse types of visual impairments, sometimes associated with additional cognitive impairments. However, for the moment we have completely omitted color blindness [15] and need to investigate this further in the future. We demonstrated that visually impaired students were successful in exploring and constructing maps using our prototype, independently of their visual abilities. Throughout the development of this project, we received positive feedback regarding the prototype by students and teachers involved in this project.

The current prototype has some limitations which we intend to further improve in the future. We plan to develop a supplementary tool that allows instructors to draw their own map and easily add audio information. Currently, map creation requires skills using vector graphic tools, such as Inkscape or Corel Draw. Most teachers and O&M instructors in our project were worried about using such tools. Several participants suggested to extend the scope of our prototype from geographic maps to other graphics and diagrams, such as mathematics, mechanics or biology. Our prototype can be adapted to other content and we plan to explore this in the future. Another suggestion made by several O&M instructors is the idea to develop a portable version of the prototype to be taken along during navigation. Our most important goal, however, is to develop a final system that is highly accessible and usable during special education classes. We will achieve this by continuing our collaboration with several international special education centers.

CONCLUSION

In this project, we designed a multisensory map for low vision and blind people. This prototype was based on a spatial augmented reality toolkit, originally designed for sighted people which we combined with audio feedback and existing tactile tools. Our work has two major contributions. First, we improved the state of the art on accessible interactive maps for visually impaired students by designing a tool that enables both map exploration and map construction (whereas most prior prototypes are limited to exploration of existing maps). Second, we rigorously applied a participatory design approach in close collaboration with students and professionals of a local special education center. This provides strong guarantees of usefulness and accessibility of our prototype. We believe that ultimately this work will contribute to improving the autonomy of visually impaired students.

ACKNOWLEDGMENTS

We thank all visually impaired participants, as well as the professionals who participated in this project, and more specifically Nathalie Garbolino (IRSA). Moreover, we thank our colleagues at Inria who helped throughout the project, notably Pierre-Antoine Cinquin, Martin Hachet, Thibault Lainé, Joan Sol Roo and Lauren Thévin. This project is conducted with the support of the Erasmus+ Program of the European Union Pr. no 2016-1-EL01-KA201-023731.

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