3D Printed Interactive Multi-Storey Model for People with Visual Impairments

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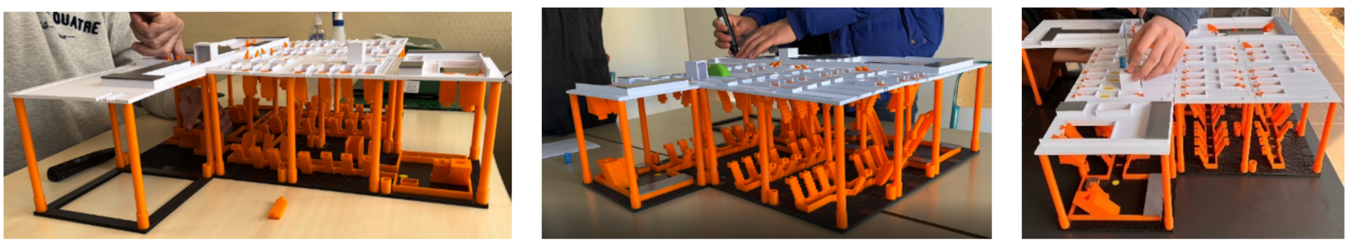

Figure 1: People with visual impairments exploring our 3D interactive model representing a multi-storey complex train station.

ABSTRACT

The understanding of multi-level spatial topologies is a difficult and frequent challenge in people with visual impairments daily life, impacting their independent mobility. Using the tools of the "maker" movement, and following an iterative co-design process with Orientation and Mobility instructors, we created an innovative tool (3D printed interactive model of a train station) for teaching complex spatial knowledge. Then, we did a comparative study with end users between the 3D interactive model that we designed and two 2D interactive tactile maps representing the same location. Our results show that the 3D interactive model is useful and usable, provides better satisfaction and is preferred to 2D tactile maps. In addition, complex spatial notions are better understood with the 3D model. Altogether, these results suggest that the "maker movement" may empower special education teachers with adapted and innovative tools.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility** ; • **Accessibility** → Accessibility systems and tools.

KEYWORDS

Visual Impairment; Spatial Knowledge; Verticality; Interactive 3D Model.

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1 INTRODUCTION

According to the World Health Organization, there are 2.2 billion people with visual impairments (PVI) in the world[1]. Independent mobility is crucial for autonomy and quality of life [26, 39, 40] as for the prevention of social isolation [3, 25]. Teaching of spatial knowledge and skills relies on orientation and mobility instructors (OMIs) and the tools that they use during their lessons. The goal of OMIs is to teach general skills and to provide enough information about a particular location for PVI to navigate independently, reliably and safely. One of the most challenging tasks for PVI is the determination of self-location in space and during the journey

[1]World Health Organization. Vision Impairment and blindness. World Health Organization. Retrieved August 3, 2022, from https://www.who.int/news-room/factsheets/detail/blindness-and-visual-impairment

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[37, 55]. This task is even more complicated when PVI must deal with a multi-storey building. Therefore, adapted tools are crucial to work on such complex spatial cases and notions.

The most used tools during orientation and mobility (O&M) sessions are tactile maps, magnet cardboards, and handmade wooden or cardboard models. Although all these tools are useful for OMIs, each of them has limitations. Tactile maps are not accessible to all PVIs, because only a few PVIs are Braille readers [2]. Magnet cardboards are versatile but are really limited in the amount of information they can display. For instance, the representation of complex places (like a building) is not accurate because magnets have simple shapes (square, rectangle, triangle). More importantly, 2D maps or magnet cardboards are 2D representations that are used to prepare for 3D navigation, which may raise significant cognitive issues. For instance, they do not - or only partially - allow the learning of complex multi-storey buildings since several floors of the same building can only be presented side by side. This makes it difficult to understand the superposition of two floors from the same building, with stairs or elevators joining two floors. All these constraints are limitations for the OMIs and affect the quality of O&M training.

In this study, we relied on "do-it-yourself" (DIY) tools and techniques that are part of the "maker movement". The maker movement is a cultural trend that places value on an individual's ability to be a creator of things. In this culture, individuals who create things are called "makers". In this study, we followed a participatory method to work on a use case (a two floors train station with multiple rooms and railways) with OMIs. Together, we created an adapted interactive model, illustrated in Figure 1, helping to teach the train station including floors, staircases and elevators joining the two floors, entrances at different levels, etc. During the co-design procedure, we first identified the OMIs' needs in order to create an interactive model that is usable and efficient for teaching. As part of this, we conducted two focus groups and two brainstorming sessions, followed by design iterations and one final discussion group.

The second part of the paper describes a comparative study between the interactive 3D model and corresponding interactive 2D tactile maps. The study involved six pairs of participants (one OMI and one student with visual impairment), that use both devices to understand a complex train station with two floors. Finally, we gathered the feedback of OMIs regarding the transfer of spatial knowledge from the classroom sessions to on-site navigation. As far as we know, this is the first study exploring the understanding of spatial knowledge in a multi-storey building with a 3D model. Our results show that the 3D model is perceived as useful and usable and is preferred over the 2D maps. According to the OMI, the 3D model is more efficient than the 2D maps for teaching the vertical organization of the building and is more efficient for PVI who do not have good spatial skills. Finally, we present another use case in a different specialized center to explore the generality and reproducibility of this approach. This companion study shows that: (i) a 3D model corresponding to another setting and other needs is much easier to make because the existing 3D files, which are editable, significantly reduce the making time and complexity, and (ii) the 3D multi-storey models are not useful for adults only but also for children who do not yet get tactile reading skills.

Our contributions are: 1) the identification of OMIs' needs to teach a complex multi-storey building, 2) a co-designed set of recommendations to make a multi-storey building based on DIY methods, 3) the evaluation of the spatial understanding and user experience with the interactive 3D model as compared to equivalent interactive 2D tactile maps, and 4) the replication of a miniature 3D model for O&M training is facilitated by existing recommendations and print files.

2 RELATED WORK

2.1 Cognitive Mapping with Visual Impairments

Cognitive mapping is the process by which a person acquires, codes, stores, recalls and decodes information about the relative locations of objects in her/his spatial environment [24]. Obviously, cognitive mapping happens in many situations such as on-site wayfinding, navigation or orientation [38] but during the observation of figurative maps and models as well; it has been shown that it is possible to transfer spatial knowledge between the two situations [13, 32].

Sighted people use visual information extensively when they mentally map places [41]. On the contrary, cognitive mapping with impaired vision relies on sequential inputs from the tactile, proprioceptive and auditory sensory modalities [12, 21, 39]. Haptic perception is the main modality that is used to create mental maps based on the exploration of tactile drawings but has a high cognitive cost [34]. Indeed, haptic perception relies on small and divided perceptual field: the ten fingertips [39]. Hence the understanding of a tactile drawing is based on spatially fragmented and serial perceptions, which must be integrated in space and time. Haptic perception of drawings requires significant cognitive resources. It has been shown that auditory information can feed mental maps too [34].

2.2 Assistive Tools for Spatial Teaching with Impaired Vision

Spatial knowledge teaching in special education centers mainly relies on OMIs. Their goal is usually twofold: to teach general skills for mastering any navigation situations, but also to provide enough information about a particular location for PVI to navigate it independently and safely. OMIs use figurative tools to teach both spatial skills and specific places.

Tactile maps – and more specifically raised-line maps – are the most used tool for teaching spatial knowledge. They can provide a clear picture of an environment layout [10, 14, 44] and they can be used for both wayfinding, orientation and mobility [44, 52]. They are used both for short-term and long-term cognitive mapping [47, 58]. Although the utility and usability of raised-line maps have been highlighted by several studies [10, 14, 26, 47, 48, 58, 59], they have several limitations. Because of the size of the Braille script, which is 6 to 10 times larger than printed text, the amount of information on raised-line maps is limited. In addition, only a few PVIs can read Braille. Another limitation of raised-line maps is the

[2]According to the WHO, there are six million people who use Braille worldwide, which is less than 1% of people with visual impairments [2]. This observation is in line with [6] and [1] estimating that the percentage of Braille readers varies between 5 and 15%.

continuous back and forth movements between the drawing and the legend, which interrupts the tactile exploration of the drawing, divides attention and, hence, overloads the working memory.

OMIs use magnetic boards and handmade cardboard models too. Magnetic boards are frequently used with a very limited numbers of magnets during on-site navigation session to represent the layout of a place. Although this tool is easy to carry and easy to use, its expressivity is very limited. The magnets are simple shapes (rectangles or circles in general), which led to over simplified representations. Cardboard models are increasingly rare because they take time to build and are fragile.

2.3 Interactive Maps for Spatial Teaching with Impaired Vision

Because of the limitations of raised line maps mentioned above, researchers have designed and evaluated interactive multimodal maps, which are also called audio-tactile maps. In such a map, the legend is replaced by audio feedback triggered when exploring the map. Brock and collaborators have shown that interactivity improves the usability of geographic raised line maps for PVIs [16]. In a comparative study between a 2D regular and a 2D interactive (i.e. audio-tactile) tactile map, they observed a better efficiency (shorter learning time) as well as better user satisfaction for 17 out of 24 participants with visual impairments. The satisfaction was mainly related to the audio interactions (instead of reading Braille), the Braille legend removal (which avoids making back-and-forth movements between the drawing and the legend), and the ease of use of an interactive tactile map. Benefits of using audio-tactile maps on cognitive mapping have also been observed by [50] and [49]. [50] assessed the cognitive mapping of 22 participants with visual impairments after they learned a 2D tactile map. More than half of the participants depicted accurate maps after learning. In a qualitative study with 10 participants, [49] showed that audiotactile maps can help elderly with visual impairments to get spatial knowledge about unfamiliar environments. Similarly, Brulé et al. designed an interactive multisensory map [18], and they showed improvement in spatial comprehension, recall, engagement and satisfaction among the students with visual impairments. But surprisingly, none of the studies on audio-tactile maps relied on OMIs' needs or gathered feedback from them.

2.4 3D printing, DIY and Empowerment of Professionals

It is possible to use additive printing and DIY tools (e.g., laser cutter) to easily make 2.1D maps (only one level of tactile relief), 2.5D maps (many levels of tactile relief) maps or 3D models [54]. It has been shown that DIY methods can empower special education teachers, because they can meet their needs regarding the heterogeneity of the population that they serve [30, 31].

Interestingly, Celani and Milan created two 2.5D printed maps with different heights of relief (stairs and walls), each one representing one floor of a library [46]. According to six participants with visual impairments who explored the maps, they are helpful for being oriented. But the authors observed that most participants had difficulties to understand how to move from the first to the second floor, since the models were displayed side by side and not over each other. This observation suggests that exploring two 2.5D maps leads to the same cognitive issues as exploring two 2.1D maps.

There are studies highlighting the benefits of 3D printed models for spatial learning for PVIs [29, 35, 36, 45, 57]. In a comparative study between 2D tactile maps and equivalent 3D maps with sixteen adults, Holloway et al. showed that not only is there a strong preference for 3D printed maps, but that 3D was better for understanding different elements that are difficult to represent in 2D (e.g., ramps, fences) [35]. In a study with eight PVIs, Leporini et al. showed that a 3D interactive model of a cultural site is perceived as a useful tool, and that 3D printing is a good technique to represent details that can hardly be perceived with other means [45].

Hence 3D models based on DIY methods are starting to be used in low vision centers. For instance, the Institut Nazareth et Louis-Braille, Quebec, CA, created a 3D printed model of a subway station, including the pathways from the street to the metro platform [7]. But, we have no information on how these models are designed and built, nor if they are useful and usable.

2.5 Virtual Environment for O&M Learning

Cognitive mapping and transfer of spatial knowledge have also been observed with virtual environments as learning tools. PVIs who learned to navigate a virtual building were able to perform orientation and mobility tasks in the corresponding real-world [27]. In another study, the virtual environment provided immersive and interactive game-based learning that was effective to transfer learned routes in the real world, but also to find alternative routes [22]. Furthermore, it has been shown that topological and metric properties are preserved from the virtual to the real environment [53]. However, despite this demonstrated interest, virtual environments are not easy to develop and use in special education settings. As far as we know, they are not used by OMIs.

2.6 Summary and research questions

To sum up, it seems that is possible to quickly make 3D models of complex places that are difficult to learn with existing 2.1D or 2.5D tactile or audio-tactile maps. These 3D models could be augmented with audio-tactile interactions (similar to audio-tactile maps). Such 3D models may empower OMIs – it is easy and cheap to make new models – and provide PVIs with more efficient and engaging tools to learn space and spatial notions. But such teaching devices should rely on the knowledge of the OMIs' needs. These observations led us to define four Research Questions (RQ) that we have addressed in this study:

RQ#1: What are the OMIs' needs to teach complex settings with multiple floors?

RQ#2: Can we create a low-cost high-fidelity prototype that meets the OMIs' needs?

RQ#3: Will the resulting interactive 3D model be more efficient and satisfying for learning spatial knowledge about a multi-storey building than the regular interactive tactile maps?

RQ#4: Based on existing recommendations and print files, can we replicate a 3D model for teaching O&M more easily?

3 CO-DESIGN OF A 3D PRINTED MODEL FOR TEACHING BUILDINGS WITH MULTIPLE FLOORS

In the first part of the study, we relied on a co-design process [42] with two OMIs. The design process included five main steps over thirteen months, as illustrated in Figure 2.

3.1 Co-design participants

In this study, we have collaborated with two OMIs (OM1, 12 years' experience; OM2, 6 years' experience) working with a local special education center for people with visual impairments. One of the researchers in the team was a blind expert in HCI who pre-tested all the 3D objects and prototypes made during the generation phase.

3.2 Exploration step: OMIs' needs for teaching a complex building with multiple floors

During the exploration phase, our goal was to address RQ#1: What are the OMIs' needs to teach complex settings with multiple floors?

For each step of the co-design process, we took notes during the sessions (the first author participated to all the sessions). At the end of the sessions, two authors summarized the results separately and all the researchers debriefed together. The debrief allowed to i) emphasize key information related to our research questions, ii) make a synthesis of the results, and iii) turn technical synthesis into recommendations.

We first conducted two focus groups with the two OMIs, which lasted on average one hour and a half each. During the two focus groups, OMIs answered the questions that we prepared in advance. Focus groups allow to collect a lot of data about the users' needs, opinions, experiences, beliefs, feelings, or concerns, in a short time [42].

In the *first focus group*, we asked open questions to the OMIs. They were invited to describe their usual working method. The discussion confirmed that they teach PVI to move independently, safely and confidently. O&M sessions are most often face to face sessions, taking place either at the low vision center, at school or on-site (e.g., metro station). The on-site sessions consist of many repetitions of selected routes (e.g., between entrance and train platform) and the identification of points of interest on these routes. On-site sessions are usually preceded by sessions at the education center, with adapted materials such as tactile maps, cardboard models, or magnet maps. Instructors confirmed that one of the most difficult settings to teach is complex buildings with several floors. The example of the train station near the city center was given as a place that is crucial for PVIs' mobility, but that is very difficult to teach. Having specific devices to teach complex multi-storey buildings was mentioned as an important need.

In the *second focus group*, we have more specifically focused the discussion on how to teach orientation and mobility regarding a complex building that includes many floors. They showed us an example of two complementary tactile maps that they use to teach the city central station (Figure 3), each tactile map representing one floor of the station. However, they mentioned that showing multiple complementary tactile maps is not optimal because it is difficult to understand that they represent different floors of the same building. In addition, they mentioned that, relying on the exploration of two maps, PVIs often fail to understand how to go from one floor to the other. Moreover, they confirmed that cognitive load related to the exploration of two complex maps with their legends is heavy and can be prohibitive for some students.

Then, we explained the concept of interactive 3D models, and we discussed about the usefulness and usability of such devices to teach complex buildings. Both professionals were convinced that they can provide learning benefits, because of the autonomy they can provide students with, but also because of their engaging and playful aspects. In addition, they mentioned that based on their experience, interactive audio descriptions added to the model would provide more independence and would probably reinforce memorization.

However, they wondered how they could get such models because they have neither the knowledge nor the tools to make them. The objective of designing together a proof of concept and questioning the making of was validated. Several buildings were considered, and they finally decided that the most relevant one would be the central railway station that they already teach with the tactile maps.

For the interactions, they suggested relying on existing tools such as the Pen Friend (©2014-2022 Royal National Institute of Blind People), which is a pen that detects labels triggering audio descriptions. The labels are self-adhesive, colorful and easily identifiable by touch. Besides, the device provides a convenient (re-)recording labelling system made for PVIs, which allows to easily adapt the feedback to the needs of each student. In line with [11], they also mentioned that they could ask students to add their own interactions, which could further enhance cognitive mapping.

3.3 Ideation step: brainstorming sessions to generate ideas

Following the two focus groups, we conducted two brainstorming sessions (between 1.5 and 2 hours each) to generate innovative design ideas [42]. During the ideation step, the OMIs were asked to describe the perfect 3D interactive model that they would imagine for teaching the railway station. All their suggestions were noted and further discussed to get more details. After the sessions, the research team organized all these details into a set of design recommendations:

Adapted level of information: As the station is very large, the interactive 3D model should contain the essential items related to navigation only, i.e., the train tracks and how to reach them with the stairs, elevators, escalators, and ramps, as well as selected points of interest (welcome desk, accessibility office, ticket sale office, toilets, etc.).

Items size and color: The OMIs requested that the 3D items (e.g., stairs) have a minimum height of 6 cm and a minimum width of 1.5 cm to be identifiable by touch. This leads to a significant increase in the size of the model if we consider the number of 3D items to be represented (48). Colors and contrasts should be added because they can significantly help users with remaining visual perception.

Model assembly: The model should not be too cumbersome. Considering the previous recommendation, the model should be made of different parts that can be fitted together. Interestingly, each part

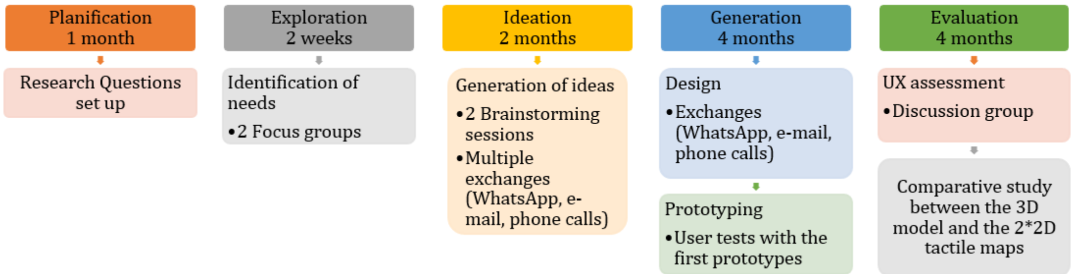

Figure 2: Steps of our co-design approach. Each step involved iterative processes.

Figure 3: Visual map of the multi-storey central station map (left) and the two tactile maps (middle and right) representing one floor each.

could be explored separately, which would allow OMIs to conduct progressive teaching with their students.

Floors exploration: The model should allow for independent exploration of the two floors (the ground floor with access to the tracks, and the underground with the many entrances and rooms). There should be enough spacing between the two floors allowing to pass the hands for tactile exploration of the underground. The height between the two floors should be adaptable to different hand sizes (i.e., two configurations with either regular or high spacing).

Pathways between the floors: The items to access the tracks (stairs, lifts, escalators, or ramps) should be separated into two pieces attached to the first and second levels respectively. Thus, when one floor is explored independently, the user can perceive half of the item on one level and find the other half on the other level.

Audio descriptions: The interactions must be easily modifiable by the OMIs and should rely on existing devices such as the PenFriend. The interactive audio descriptions must be adaptable to the user (i.e., age, visual impairment, and skills in O&M) and provide at least two information levels: basic descriptions and advanced descriptions with more details.

3.4 Generation step: Making of the 3D model prototype

During the generation phase, our goal was to address RQ#2: Can we create a low-cost high-fidelity prototype that meets the OMIs' needs?

3.4.1 Materials and prototyping. Our goal was to address OMIs' needs by making a low-cost high-fidelity prototype. We used the free version of the Autodesk Fusion 360 software for modelling the elements of the model. In terms of hardware, we used a Creality CR10-v2 3D printer with PLA filament. For creating the 3D models, we used the maps of the station that are available online, but we also went onsite to take photos when details were missing. Thanks to 3D printing, we were able to make many trials in a short time to answer specific technical and functional questions regarding the model. For instance, we observed with the expert participant (blind adult) that four steps were not enough to easily identify half of a printed staircase. Hence, we doubled the number of steps (8 steps, 4cm height total). With the same method, we selected the height (10 mm) and thickness (3 mm) of the walls, as well as the spacing between the walls and the stairs (15 mm) to make exploration and recognition of the different items easy. We slightly increased the thickness of some items (e.g., wall thickness from 1.5mm to 3mm) to make sure they can resist to a bumpy exploration.We created small removable pillars in order to modify the vertical spacing between the two floors. We tried different textures for providing meaning to different areas of the station (e.g., accessible vs. non-accessible areas).

We created two difficulty levels of tactile exploration with the same model by adding or removing covers above some rooms. The "easy" model (with covers, Figure 4 left) shows essential information only (pathways and points of interest). The "complex" model (covers removed, Figure 4 right) allows the user to explore additional rooms and places in the station.

Finally, we conducted informal tests at the lab to ensure that: i) the spacing between the floors is appropriate when using the

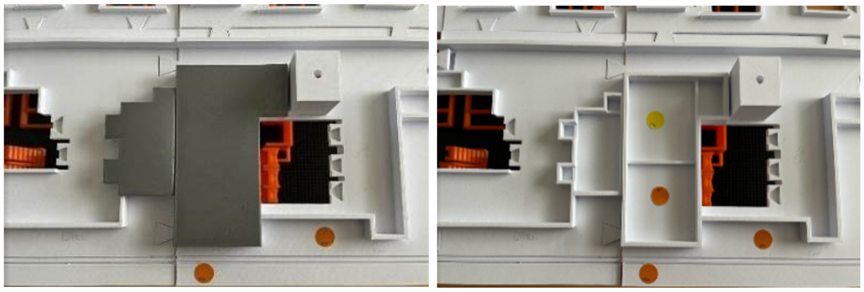

Figure 4: Increasing the complexity of the tactile exploration of the station. Left: the covers hide some details. Right: when the covers are removed, the model shows many more details (e.g. room configuration).

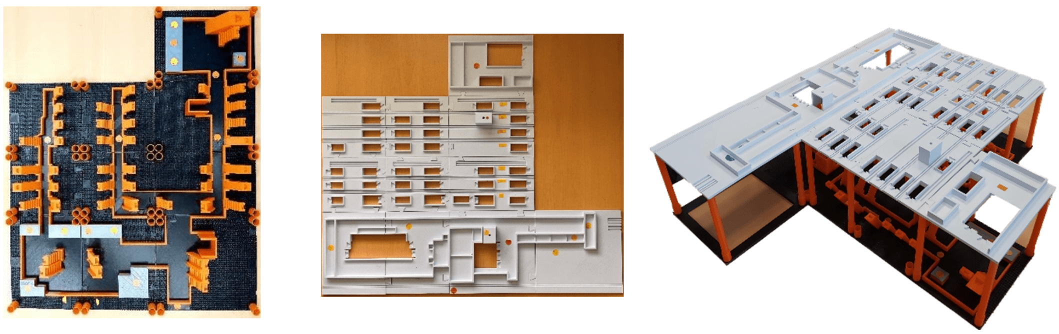

Figure 5: Left: Underground level, Middle: Ground Floor, Right: high-spacing (18 cm) complete model.

PenFriend, and ii) the labels are identifiable by touch when placed onto the plastic (PLA) textures.

All these decisions were made with the OMIs. During the making of, we shared photos and questions by text messages, emails or phone calls. In addition, despite their busy schedules and the conditions levied by the Covid19 pandemic, they welcomed us at the center to provide recommendations about the textures and the different 3D printed items.

3.4.2 Final prototype and debriefing. The final model was made of two floors and twenty-two parts that can be used independently, and that can be put together for building the whole model (Figure 5). The overall size of the assembled model is 66*57*10 cm or 18 cm height depending on the spacing between the floors.

The cost of the material used to build the model was: for PLA filament rolls (≈ €15 each); PenFriend with 138 labels (€149).

After presenting the prototype to the OMIs, we organized a final discussion group to gather feedback about it. We prepared a semi-structured interview adapted from a Venkatesh and a meCUE[3] user experience questionnaires [43, 61]. The questionnaire was sent by email in advance so that they could think about the answers (spontaneous response was not required). The discussion group took place at the education center and lasted nearly two hours during which we were allowed to record the responses.

The interview was transcribed and summarized during a debrief session including all of the researchers. The interview provided interesting and meaningful findings. The professionals mentioned that the model would be useful not only for preparing locomotion sessions at the station but also for introducing complex spatial skills to PVIs, such as *"horizontal and vertical directions of travel, the difference between escalator and elevator, an elevator that opens from different sides on each level, etc."*(OM2). The instructors enjoyed the adaptability of the model citing the different parts, heights and provisions but also the different levels of complexity and interaction that are provided. They mentioned that *"the interactions make the model adapted to a great number of children and adults according to their ages and skills in O&M"* (OM1). They said that considering the initial size of the station, the size of the model is good: *"smaller, we would not have been able to introduce needed details, and larger, one would not be able to understand the globality of the station"*(OM1). They underlined another benefit of the model: indeed, some PVIs think that when they move, the building moves with them, whereas *"on the model, one can move a virtual persona on the two floors and understand that the building is fixed"*(OM2). Finally, they said that although it is important to start with the model, students must go on-site because mental mapping of space is also dependent on mobility experience.

[3]http://mecue.de/english/home.html

4 USER STUDY: TWO INTERACTIVE RAISED-LINE MAPS VS. ONE INTERACTIVE MODEL

Following the participatory design of the tool, we designed an experimental study to answer RQ#3: is the interactive 3D model more usable and satisfying for learning spatial knowledge about a two-floor train station than two interactive 2D tactile maps?

4.1 Participants

We recruited four additional OMIs for the user study. The four instructors have respectively 12, 8, 20 and 10 years of professional experience (see Table 1). All the OMIs were volunteers recruited through two special education centers geographically close to the research laboratory and that were informed of our study. We had a preliminary call and meeting with them to introduce our study and present the 3D model.

The participants with visual impairments were selected by the OMIs among their students. The selection criteria depended on the OMIs. They chose students who want to learn the railway station and have the required skills (at least fair, see Table 1). Participants accepted to replace their regular sessions by three sessions in the framework of this user study. We finally got six pairs of participants involving five different OMIs and six PVIs (see Table 1).

All the OMIs were familiar with the central station because it is an important place that they frequently teach to PVIs (anyway, all the OMIs mentioned that they always explore a new building before teaching it to PVIs). Some of the PVIs were familiar with the train station (P3: 1 or 2 trips per week, P4: dozen trips during a year, P1,2,5,6: rare travels).

4.2 Material

We prepared the material for the study with OM1 (who was already involved in the co-design process). It includes our interactive 3D prototype and two raised line maps (ground floor and underground) created by a tactile document maker at the same specialized center (see Figure 6) [4]. As a reminder, the size of the model is 66*57 cm. The size of each map is 29*20 cm. We added the same PenFriend-based interactions onto the model and the tactile maps. We put 17 labels on different landmarks (entrance, train platforms, etc.) according to the needs of the OMIs. The PenFriend detection of the labels launched the name of the corresponding landmark (ex: "entrance hall 1, underground"; "entrance hall 1, ground floor"; "tramway stop", "toilets"; etc.) and audio description: "Access to Platform for Tracks X and Y", "Platform for Tracks X and Y", etc.

4.3 Protocol

Typical O&M sessions when preparing a journey frequently focus on teaching three spatial knowledges: i) the identification of specific landmarks, ii) learning routes between different locations, and iii) mentally mapping the overall configuration (survey knowledge). We designed the experimental protocol with OM1 and OM2, having these different aims in mind.

The experiment was divided into three sessions one week apart from each other: two map exploration sessions (one with the 3D model and the other with the 2D tactile maps, counterbalanced according to the group) in the classroom, followed by one on-site navigation session. All these sessions were followed by a semistructured interview (Figure 7). The two exploration sessions aimed at understanding: i) the advantages and drawbacks of each device over the other, and ii) if there are significant differences of spatial learning when using each device. The third on-site session aimed at assessing which device was more efficient for the knowledge transfer between the classroom session and the on-site session.

Figure 6: Ground floor represented on the Interactive tactile map (left) and Interactive 3D Model (Right).

We designed a within-subject study which requires fewer participants and minimizes the random noise related to each participant[4].

4.3.1 Classroom sessions. Before starting the experiment, the instructors were told that they should feel free to conduct a real O&M session with their student according to his/her needs and abilities, but they were asked to achieve the same goals, i.e. teaching landmarks, routes, and some knowledge about the overall configuration of the train station. Together, we specifically prepared a set of questions regarding landmarks, single-level paths and two-level paths (mandatory level change), as well as general orientation (e.g.: "Can you show me where is landmark X?"; "How do you go from the entrance Y at the underground floor to the platform Z at the ground floor?"; "when you are facing the office, in which direction is Hall 3?").

Each exploration session started with a familiarization phase during which the instructor and the student were free to play with the device (3D model or two 2D tactile maps). When the instructor considered that the student is ready, she started to teach landmarks, routes and the overall configuration of the station and then she asked questions about the three types of knowledge. After each of the two exploration sessions, we conducted a semi-structured interview with each PVI (see Figure 7), using a slightly adapted meCUE questionnaire [43] to assess the four following dimensions: I. Perception of Instrumental Qualities (usefulness, usability), II. Perception of Non-instrumental Qualities (visual aesthetics, status and commitment), III. User Emotions (positive and negative), IV. Consequences of Use (intention to use and product loyalty). We also asked the participants about their comments and preference regarding the devices.

4.3.2 On-site Session. Finally, the instructor was free to conduct the on-site session as usual. We took some notes regarding the PVI's behavior during the session, and we conducted two semi-structured interviews with the student and OMIs after the session. We asked

[4]https://www.nngroup.com/articles/between-within-subjects/

Table 1: Details of the PVIs. *spatial skills as evaluated by the OMIs on a five-level scale (Excellent, Good, Fair, Poor, Bad)

Participant ID	Age	Gender	Visual impairment	Tactile reader	Spatial skills*	Experimental Group	OMI ID
P1	17	M	Blind	Yes	Fair	A (maps first)	OM1
P2	17	M	Blind	Yes	Good	A	OM1
P3	55	M	VI		Fair	B (model first)	OM3
P4	56	F	VI	Yes	Excellent	B	OM4
P5	45	M	VI		Fair	A	OM5
P6	23	F	VI	Yes	Fair	B	OM3

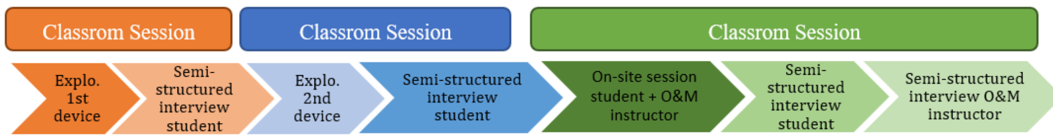

Figure 7: Protocol of the user study.

questions about i) the perceived knowledge transfer between the device exploration and on-site navigation; ii) the perceived usability of each device (subjective advantages and drawbacks) to teach two floors building, and iii) the impact that each device may have on their teaching methods, their intention to use, and how they would improve the devices to make them more efficient.

4.4 Collected data and Analysis

We obtained informed consent from all the participants (guardians of children under 18) to record the exploration sessions (audio and hands images) and interviews (audio only).

After the two classroom sessions, participants were asked about their preferences between the two devices. The answers have been recorded, transcribed, and gathered in a table in order to highlight each participant's preference and reasons for their choice. Then, a debrief session with the whole research team aimed at summarizing the relevant comments regarding both devices.

During the on-site session, one researcher was following the pairs at the railway station and wrote reports with observations made during the on-site session. The collected data included behavioral observations and comments related to the ongoing session as well as comments related to the previous classroom sessions and the devices. The reports were then summarized and discussed with the whole research team.

The semi-structured interview with OMIs were recorded and transcribed for thematic analysis [5].We reduced the data in three steps: i) one researcher gathered the data in a table (rows corresponding to participants and columns to the questions' topics); ii) two researchers worked separately on the table, gathering the comments that were relevant (everything concerning the impact of the devices on their professional practice); iii) themes were identified by the two researchers and discussed with the whole team. In addition to the observations, we collected data regarding the OMIs' skills. They had to answer a set of questions regarding the frequency of use of different tools: tactile maps, wooden mockups, 3D models (representing an environment), 3D objects (ex: 3D-printed sidewalk), magnetic cardboards and software (InkScape, Adobe Illustrator, Fusion 360, TinckerCAD, StechUp, GIMP) on a Likert scale with 5 levels (from "never" to "everyday use"). They also had questions about their making skills (if they are autonomous or need assistance).

5 RESULTS

In the results section we use the following abbreviations: "2DM" for the interactive 2D maps and "3DM" for the interactive 3D model.

5.1 OMIs IT skills and Frequency of use

The survey with OMIs shows that the magnet board is the most used teaching tool (Figure 8). Other tools are less used because of the lack of time and skills. For example, OM5 said that: *"Despite the benefits of these tools, they require time (all the tools expect magnet board) and we lack it most of the time"*. Concerning 3D objects and models, OM3 and OM5 use Lego bricks, OM5 also uses cardboard boxes. OM1 and OM4 collaborate with makers for the making of 3D-printed objects (see Figure 9). 3 out of 5 OMIs would like to learn (OM4,5) and improve (OM1) 3D modelling and printing skills. Regarding frequency of use of different software, OM1 uses TinkerCAD and GIMP several times a year and OM4&5 use SketchUp and InkScape respectively but they are not autonomous.

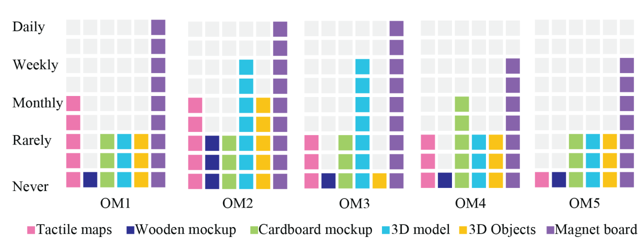

Figure 8: The frequency of use for each tool and OMI.

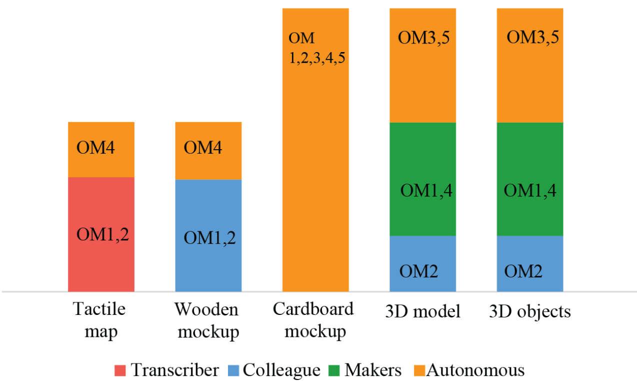

Figure 9: The required assistance for the creation of each tool.

5.2 PVIs semi-structured interview following the classroom sessions

5.2.1 PVIs preferences between the two devices. All the participants preferred the 3DM for different reasons: *"I could better recognize items and it was more efficient"* (P1), *"because it was more efficient and useful"* (P2), *"because 3DM was more efficient, pleasant and useful"* (P3, P6), *"it is more useful because of the 3D"* (P5). P6 added that *"It allowed me to develop something that I do not usually have, which is a mental map. I have a complete understanding after the 3D model exploration, which is very difficult for me to get with the tactile maps or when being on site"*. Similarly, P4 thinks that the model is more efficient because it is *"more representative, playful and provides a better representation of the environment"*; but she added that 2DM was more pleasant because she likes the perception of 2DM textures, which is not the same in 3DM.

5.2.2 MeCUE - Perception of instrumental qualities: Ease of use. **Interactive tactile maps (2DM):** 4 out of 6 participants (P1, P2, P4 and P6) considered the use of 2DM easy but with limitations. The main one was related to tactile reading and more precisely to texture recognition. For example, P4 and P6 could barely distinguish between track and platform textures; P3 could not recognize the stairs and tramway lines; and P5 could not find the entrances because he was confused about textures. P2 mentioned that it was difficult to switch between the two maps for answering the 2-level route questions.

3D interactive model (3DM): The 3D model was perceived as easy to use for all the participants. P4 found that the train tracks, platforms and stairs are well represented. Difficulties were mentioned concerning the spacing between the items (P3: *"one must have thin fingers for easier exploration"*) and the location of pillars (P5 *"some items were more complicated to find because of the pillars"*).

5.2.3 MeCUE - Perception of instrumental qualities: Usefulness. The audio interactions were perceived as useful for all the participants and for both devices.

Interactive tactile maps (2DM): Only two out of six participants found the 2DM useful to understand the spatial organization of the three corridors of the underground floor (P3) and train tracks (P2). P3 qualified the map features as *"adapted, helpful and clear"*. The other four participants (P1, P4, P5 and P6) were uncertain regarding the usefulness of 2DM. Still, they confirmed that they learned things about the station layout they did not know before.

3D interactive model (3DM): All participants considered 3DM as useful and claimed to have learned new knowledge. Participants related the 3DM utility to different factors: better recognition of items (P1, P4), understanding of the global layout (P2), the feeling of being *"more comfortable"* and *"quicker"* (P4) and *"cognitive mapping creation of the railway station with only one session"* (P6).

5.2.4 MeCUE - Perception of non-instrumental qualities: External perception of the tool. This section of the questionnaire gathers participants' feeling about the device and whether they would use it in presence of their classmates, friends or family.

Interactive tactile maps (2DM): Four out of six participants (P2, P3, P4 and P5) felt ready to use and showcase the 2DM to their peers. P5 said that "It may even help some of his colleagues (those with visual impairments)". P4 said that it would be a "fun" experience. P3 said that he would be happy to showcase, but only if he is able to explain it correctly. P1 was not able to decide if he would be embarrassed or happy to show the 2DM to his classmates because they do not have visual impairments. He had no idea about what others could think about it.

3D interactive model (3DM): All participants said that they would be happy to present the 3DM to their peers. They gave the following reasons: control over the device (*"I am able to manage the discovery"*, P1), pride (*"my wife would be proud of me"*, P3), positive outside view (*"my friends would found it awesome"*, P1), fun (P6) and usefulness (*"I think that they would find it very useful because, afterwards, they could explain to me if we have to meet somewhere, show me on the model. . . And if we do not have the model with us later on, they can have a more general idea of what I perceive. We can better understand each other."*, P6).

5.2.5 MeCUE - Perception of non-instrumental qualities: Aesthetics and design improvement. **Interactive tactile maps (2DM):** Suggestions of improvement concerned the textures and the visual contrast. Improvement of textures was raised by five out of six participants (all except P5). P4, P3 and P6 had difficulties concerning texture discrimination and suggested making them easier to recognize or reducing the amount of information. P3 found the ground floor map very crowded, and he suggested to make a larger map with more empty spaces. P2, P4 and P6 would prefer to have a braille legend in addition to audio feedbacks. P5 suggested to work on colors and contrasts.

3D interactive model (3DM): Four out of six participants (P3, P4, P5, P6) mentioned the need to add tactile symbols to indicate the access doors. P6 suggested adding contrast between the floor and the top of the walls. P3 and P6 wished to mention the location of the tactile guidance strips because it is a very important landmark. P1 suggested larger railways and P4 suggested to better fix some items that fall during exploration.

5.2.6 MeCUE - User Emotions: Positive and Negative emotions. **Interactive tactile maps (2DM):** All participants were happy for having used the map. P4 mentioned feeling well with the 2DM, because she *"needs to touch the relief and imagine what it can represent"*. Other participants mentioned negative emotions: tiredness (P3, P4, P6), anger, frustration, and bore (P3).

3D interactive model (3DM): All participants were happy with the 3DM. P4 expressed that: *"Touching the model is very useful and pleasant . . . I enjoyed the discovery of the 3DM and. . . I spent a very very good time!"*. The only negative emotion felt by two participants (P4 and P6) was tiredness. However, P4 said that it is related to her health condition, and P6 mentioned that it was less tiring compared to other O&M sessions *"because there was a playful aspect, a bit of fun"*.

5.2.7 MeCUE - Consequences of use: Loyalty and Intention of use. After each session, participants were asked if they would choose the device that they just used (2DM or 3DM) in addition to the other regular devices (maps, magnet board, etc.)

Interactive tactile maps (2DM): Three out of six participants (P3, P4, P5) wish to use 2DM during other O&M sessions if there is less details (P3, P5) and higher contrast (P4). The other three participants showed uncertainty about the future use of 2DM, because it requires a lot of concentration (P1), it is difficult to imagine what the tactile map represents in reality (P2), *"This only device is not sufficient for learning"* (P6). However, if they would use it, it would be for history and geography (P1), or simple crossroads (P6).

3D interactive model (3DM): All the participants were positive about using 3DM during future O&M lessons. P1 and P2 said that they would like to work with 3DM first and, then, go for on-site sessions. P1 mentioned that he would prefer 3DM for complex buildings such as railway stations or airports. Different participants mentioned that they would love to get 3DM representing their favorite places: soccer stadium (P2), city airport, city library, Departmental Council, and Departmental Office for People with Disabilities (P4). P6 said that it would be nice to have 3DM for all the O&M sessions and all the buildings: *"As soon as you have to discover a new setting, the university for example. If we can make a model of the university and the office for people with disabilities can keep it, it would really be great"*.

5.3 Observations made during the on-site session

All the sessions were quite similar: the instructors started with a short reminder and questions about the layout of the railway station. Then, participants were asked to find the landmarks and go along some routes. Instructors asked a lot of questions to make sure that the students are aware of their location and orientation. All the OMIs were satisfied with the on-site session. In the following two paragraphs, we report observations made about the two devices during the on-site sessions.

About the 2DM: Following the 2DM classroom session, the OMIs brought the 2DM, in case the participants wanted to explore it when being on-site. Two out of six participants needed to explore the 2DM at some points during the session. P1 was not sure about his orientation and the instructor proposed to check on the 2DM. The instructor orientated the map in register with the station (see Figure 10 right) which allowed P1 to remind some features about the layout of the railway station. He was then able to continue the route with more confidence. P4 wished to explore the 2DM because she was confused by the number of stairs to the train platform and the direction of the escalators. Thus, she checked the location of the stairs on the 2DM and she walked to the escalators for checking. OM3 offered P3 to quickly explore the map because he could not self-locate at some point. P3 refused, saying that *"it is too difficult for me"*.

About the 3DM: The first task of P1 was to reach one of the landmarks (the office for people with disabilities), but he could not remember its location. The instructor gave the recommendation *"Imagine yourself in the model"*, after which P1 said: *"OK, it's straight ahead, I'm going to cross the 1st hall, the 2nd hall and the corridor and get there"*. Then he did the route with success. P3 said *"the model helps me a lot" and that he would not be able to perform the tasks without having "the representation of the 3D model in mind"*. At some point, P3 felt lost in hall 1 and wished to get the model to explore it and remind some elements. OM3 illustrated the escalators and stairs touching his hands (see Figure 10 left and middle), and she said *"this is where I would need a set with 3D objects"*. P4 and P6 said that they are mentally imagining the model to do the routes and survey exercises.

5.4 OMIs' feedback and semi-structured interview following the on-site session

The OMIs considered the two devices as useful and complementary for the on-site session. According to OM5, 2DM and 3DM allow a *"complete discovery"*. However, 3DM turned out to be more useful for participants who do not have a remaining functional vision and only average spatial orientation skills (P1, P3 and P6). According to OM1 and OM3, the 3DM helped P1 and P3 to perform better during the on-site session. They explained that despite numerous previous O&M sessions (on-site and with a tactile map for P1, with a magnetic board for P3), they never performed as well, and that P3 has never worked on two levels simultaneously. In addition, OM3 pointed out that the cognitive mapping is hard for P6 but after the 3DM session she was *"much quicker and more efficient"*. As mentioned, all the OMIs said that both devices were useful to prepare the on-site session. However, in general, 3DM was judged as more efficient than 2DM. This observation was confirmed during the semi-structured interviews. 3DM was evaluated as more intuitive and providing better independence. All the OMIs think that it was easier for their students to understand the pathways between the two floors with 3DM.

Following the thematic analysis, the identified themes were the following: Teaching *"verticality"* notion, Usage autonomy, Comfort, Complementarity of the devices, and Transportability.

Teaching verticality notion: According to OM1, OM3, OM4 and OM5, it was easier to teach the verticality notion with 3DM. Talking about P1, OM1 added that *"It was less needed to support him for understanding the pathway between the two levels. The model was immediate and intuitive"*. Regarding the 2DM, OM1 mentioned that: *"There are both solid and broken lines. . . And to distinguish the open areas, even if there is a different texture on it, it was difficult for him."* OM3 (P3 and P6) mentioned: *"In my opinion, it is indisputable. Teaching these notions is very problematic with tactile maps"*. P4 started with the 3DM and according to OM4: *"the 2-level routes were*

Figure 10: Photos during the on-site session illustrating P3 and OM3 (left and middle), and P1 and OM2 (right).

intuitive for her", then *"she could also do the 2-level routes on the map because she has a very good spatial representation, but it was a bit more tedious and required more time"*.

Usage autonomy: OM4 considers that 3DM was more intuitive and provided P4 with more autonomy: *"she was an actress of her discovery session"*. The interactions also add more autonomy since *"the person can check if she/he is in the right place, it's playful"*. They agreed that adding legends to the maps would provide more autonomy.

Comfort: OM1 and OM4 made the similar observation that less explanations are needed with the model. OM1 stated that *"as an instructor, the model gave a comfortable feeling"*. For example, she does not need to explain orientation in relation with a specific landmark, since it is obvious with 3DM. OM3 said that it is comfortable that the 3DM is *"quite modulable, that you can add or remove things (covers)"*.

Complementarity of the devices: OM5 and OM1 think that the two devices are complementary. They say that 2DM can provide a good mental mapping of the station and localization of the entrances, while the model allows to go into more details and understand the pathways between the floors.

Transportability: All OMIs consider that it is easier to bring 2DM on-site. But all of them also mentioned that they would like to get a set of prototypical 3D items (elevators, stairs, escalators, etc.) to bring on-site.

6 REPRODUCTION IN ANOTHER CONTEXT

At the end of the previous study, we aimed to assess to which extent these results are generalizable and reproducible. We addressed RQ#4: *Based on existing recommendations and print files, can we replicate a 3D model for teaching O&M more easily?*

We designed a qualitative companion study based on a use case in a different setting. We met another OMI from another special education center in another city, with a professional experience of fourteen years. We showed her the interactive 3D model of the train station. She enjoyed the stacking of the floors which *"can help to teach building with multiple floors"*. She was very enthusiastic about having a 3D model for her classes and added that since she is working with children under 10, it could be a playful but at the same time very useful tool. She asked for a 3D model representing one part of the low vision center she works in. She did not mention any modifications except recommendations regarding textures and color contrasts. The making of followed a similar iterative method and took one month: two discussion sessions with the OMI and blind end-user of 1.5 hours each, between 20 and 25 hours of modelling and 60 hours of 3D printing (Figure 11).

The model was tested with four children with visual impairments. The procedure of the session was adapted to their age and skills by the OMI. After the sessions, we conducted an interview with the OMI to gather her feedback. According to the OMI, the interactive 3D model is less abstract and can be presented to a wider audience. She said that with tactile drawings she needs to explain the meaning of each symbol, whereas with 3DM it is intuitive. She claimed that the 3D model makes it easier to understand the notion of verticality, and is very useful for both survey and route questions. Indeed, she mentioned that 3D is directly linked with the sensory experience of PVI and makes cognitive mapping less abstract. She also wished to use 3D models because it is easier to represent spatial configurations (i.e. a corridor).

However, she said that despite the benefits of the model she must use other devices (magnetic boards) because they are more available. In addition, the OMI was not familiar with the PenFriend and was not sure that the children would be able to handle it easily since they have never used it before. After the classroom session with the children, she said that, finally, the audio descriptions were engaging for them, and that they wanted to reach the corresponding locations immediately. The 3D model was playful and enthusiastic for the children.

7 DISCUSSION

7.1 Learning space with interactive devices

Our results showed that the 3D interactive model is efficient not only for the PVIs who rarely go to the railway station but also for those who are familiar with it. For instance, P3 weekly goes to the railway station but always relies on the accessibility service and has never been able to do 2-level routes on his own. He was able to realise two-level routes after the 3DM exploration. P6 takes the train on rare occasions only, and relies on family or friends when she does. After exploring the 3DM, she mentioned that she now understands the spatial organization of the station. P4 was familiar with the railway station before renovation. During the classroom session, she mentioned that we made a mistake in the 3DM. Once in the station, she went to this specific location and understood that the 3DM was correct. Thus, even though the on-site session was after the sessions of 2DM and 3DM, according to participants and their OMIs the 3DM had a real impact on their comprehension and navigation on-site. A long-term study should assess the learning effects with 3D interactive model.

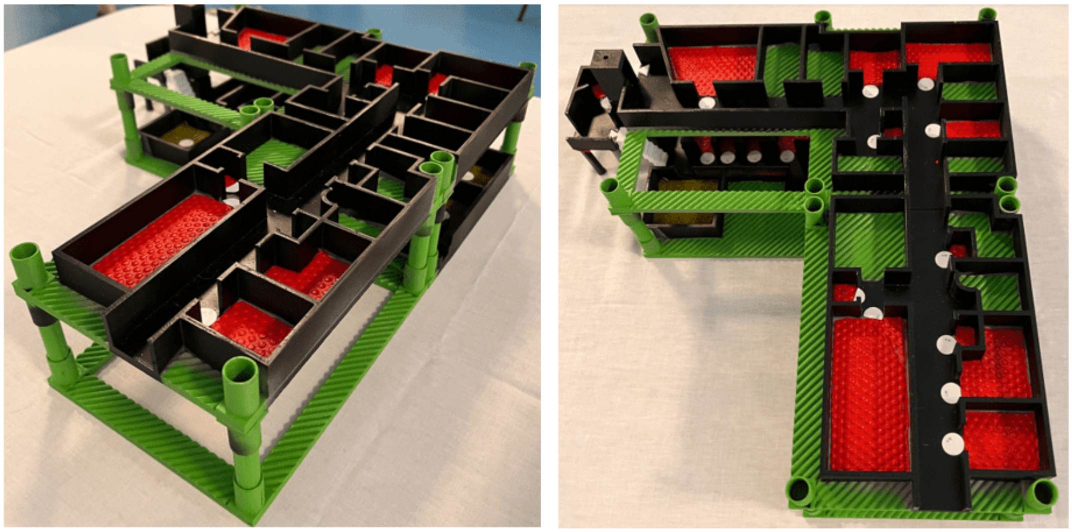

Figure 11: 3D interactive model of the second special education center.

At the end of the classroom and on-site sessions, we got valuable feedback about the impact of using 3D interactive models for learning space. The pairs (OMI and PVI) that participated to this study were used to work together and they had previous O&M sessions together. Hence, OMI feedbacks were based on reliable knowledge about their student' spatial skills. Numerous comments underlined that the interactive 3D model helps the students to build or improve a mental map of the station. However, these results are in line with studies showing that interactive 2D maps have a positive impact on spatial learning too [49, 50]. Therefore, the improvement of learning could be due to the interaction only, independently of the device being used (2D maps or 3D model).

7.2 3D Interactive Models vs. 2D interactive tactile maps

Using 3D models offers inner advantages compared to 2D tactile maps: 3D printed models can present different levels of details, and 3D printed objects are more durable than 2D tactile maps [20, 33]. Our results with the six blind adults show that 3D models including objects and textures are easily recognizable and that there is no need for an additional Braille legend. Our participants qualified the 3D model as easy to use, obvious and intuitive. The observation is different for tactile maps. Indeed, four of them were tactile readers and, however, three of them needed a Braille legend in addition to audio feedbacks. Our interpretation is that 2D maps are not as self-explanatory as 3D models. Therefore, users need additional explanations through a legend.

In our study, interviews with OMIs were carried out at the end of the three sessions which might have affected the clarity of recall. We used this experimental design because OMIs were extremely limited in time, and it was impossible to conduct interviews after each session. However, as mentioned in the methods, the protocol was designed with them, so that they were able to prepare the recall session by taking notes regarding the advantages and drawbacks of each tool.

Our results are consistent with previous research about the preference for 3D objects. A study with sixteen PVIs showed a strong preference for 2.5D maps as compared to tactile maps [36]. Another study with five PVIs showed a preference for 3D tangible content over braille-based content [28]. Moreover, it has been shown that PVIs show a better time efficiency in recognition of 3D symbols compared to 2D [15, 33]. In addition, our second prototype for children under 10, who are not braille readers, confirmed that 3D interactive models are usable for a diversity of users.

However, we cannot exclude that some of our findings concerning the differences between 2D maps and 3D models might be linked to the manufacturing process rather than their spatial configuration. As an example, 3D printers can provide finer details that might aid users to tactually recognize train tracks, but this is a separate consideration from being able to maintain spatial accuracy by stacking individual floors on top of each other. We do not think this is an important effect in our study because our 3D model included two textures only: one specific texture for non-accessible areas and one texture for the other areas and items, which were asked by the OMIs during the co-design sessions. However, it would be possible to definitely exclude the manufacturing process effect with a study comparing the learning of a multi-storey building with two separate 3D printed maps displayed next to each other versus a 3D printed model (with superposed maps).

In conclusion, a vast majority of the OMIs and PVIs we have worked with prefer 3D models, especially for understanding spatial notions in 3D, but they mentioned that it is a complementary teaching tool that is less portable. In addition, they are concerned with the making of, because it requires specific knowledge and skills.

7.3 Making of 3D Interactive models

The survey with the OMIs shows that the most used tool overall is the magnet cardboard. However, 3D models and objects are frequently used by OM2 and OM3, which is in line with the ongoing experience in the Louis-Braille center, Quebec, CA [7]. Surprisingly, these two professionals do not want to learn 3D modelling, which can be explained by the fact that they already use Legos. Contrary to them, OM1, OM4 and OM5 want to learn 3D modelling. Actually, OM1 is part of a local network of makers, who are creating and sharing 3D models in a free and open-source website. OM4 is collaborating with a local rehabilitation center that has set up 3D workshops with three main objectives: (i) for the patients to acquire skills; (ii) increase their chances to get back to work; and (iii) answer the needs of other patients more quickly (e.g. spare parts for a wheelchair).

All the instructors from the main study and case study were interested in using 3D miniature models in their daily practice if they were available. Three of them would like to learn 3D printing to be able to make similar tools on their own. The others were not convinced about having time and skills for it. This result is in line with previous research [19] that indicates that some specialized teachers think that modelling and printing is not their job, while others are interested in learning 3D printing techniques. The results are also in line with [35] where six out of seven OMIs were interested in creating and using 3D objects. In general, concerns about DIY techniques were raised by professionals of disability in several studies [17, 60, 63]. Vandenberghe et al., investigated maker technologies for empowering occupational therapists and they claim that infrastructural changes (funding, availability of professionals, etc.) must be addressed before being adopted [60]. A survey with seven OMIs showed that they perceive the 3D printed materials as a powerful tool for teaching key concepts and skills in O&M training (such as street crossing), because they consider them as engaging and efficient as compared to existing tools [35].

Based on three arguments, we are convinced that OMIs can short-term be empowered by 3D printing technology: (i) Our case study in another professional setting showed that the existence of a library of objects significantly facilitates the making of a 3D printed teaching model and drastically decreases the time needed to make it. Thus, we fully agree with [19] suggesting that some of the obstacles can be overcome, especially using open-source databases of 3D models of numerous objects (see e.g., the Thingiverse or Btactile databases). In addition, all the OMIs from our two studies have access to 3D printers or local FabLabs, and two of them have already experienced 3D printing (OM1 already made 3D models and OM4 ordered 3D objects to a FabLab). (ii) Having concerns regarding the making of 3D models and objects is legitimate, but the making of 2D tactile maps requires specific skills too [62]. The survey showed that some of the OMIs involved in our study do not know how to make their own tactile maps and rely on an expert making tactile documents in the center (the transcriber). Informal discussions that we had with transcribers following this study showed that they would be interested in making 3D modeling and printing, and that they would consider this task as part of their duty. (iii) A recent systematic review [56] about the making culture for accessibility revealed that individuals can be empowered if they are provided with accessible workshops (instructions and inclusive communication [9]), materials [23] and support from the community. Almost half of the research papers (47%) included in the review are focused on PVIs, meaning that the implementation of good practices and methods can empower OMIs and PVIs. For example, Brulé et al., in a long-term study, showed that low-vision professionals actually use laser cutters and judge them as versatile and flexible tools [17]. In conclusion, it seems that 3D printing and laser cutting are complementary techniques that professionals will be able to rely on in the near future. This is probably even more true as research is making progress in the automatic transition from a 2D file to a 3D file [19]. Based on all these converging observations, a future study should address the ability of OMIs to make their own tools after being instructed about existing databases of 3D models, as well as being taught basic 3D modelling and 3D printing notions.

7.4 3D objects for on-site sessions

Tactile maps and magnetic boards can easily be brought in a bag, which is not the case for a large 3D model. In our study, two participants used the tactile maps and one participant used the magnetic board during the on-site session. In addition, one OMI used her fingers to represent stairs and mentioned that it is a perfect illustration of how 3D printed objects could be used on-site. All the instructors would like to have a portable set of 3D objects. A set of 3D objects would be a bit cumbersome but much lighter than the magnetic board, and according to them, it would help a lot during on-site sessions. Interestingly, the same set of 3D files could be used to print the set of portable objects but also for printing the objects constituting the interactive model used in the classroom.

7.5 Interactive 3D models or virtual environments

As mentioned in the relatedwork section, there is evidence from several research studies that PVIs can create and transfer spatial skills and knowledge from virtual environments to the real world [27]. Nevertheless, the development of an immersive virtual environment requires significant technical skills compared to 3D printing. In addition to creating the virtual environment, OMIs will face the challenge of using it during training sessions and troubleshooting bugs. Hence, we are convinced that the use of interactive physical models is a simpler and more immediate method than the use of a virtual environment for O&M teaching. This being the case, it would be interesting to compare the advantages and disadvantages of both in a comparative behavioral study. Thus, a future study may evaluate the difference between learning with an interactive 3D physical model and its equivalent in a virtual environment and assess whether there is a significant difference in acceptability, learning time and effort, as well as cognitive mapping.

8 CONCLUSION AND FUTURE WORK

This study showed that interactive 3D models are a complementary, useful and usable tool for spatial learning, especially for 3D spatial notions. There are three important changes that the interactive 3D model brought to the OMIs that we observed. First, they consider that the 3D model is more intuitive, requires fewer explanations, and thus allows PVIs to learn spatial knowledge on their own. Second, considering the autonomous navigation in a complex building with multiple storeys, the OMIs confirmed that the 3D model shortened the learning time. Finally, such complex buildings are usually not studied with children having low tactile reading skills. Indeed, reading multiple 2D tactile maps is considered as too difficult for them. Because the 3D interactive model is playful, intuitive and self-explanatory, the OMI considered it was appropriate to teach a complex building with it.

We are confident that the numerous online databases, tools and methods [8] but also the existence of numerous local FabLab can support the spreading of such tools in the special education community. However, we made two observations in our study that would be worth future work. The first suggestion would be the creation of a dedicated library of objects (staircase, escalator, etc.) that could be used by themselves to learn specific knowledge (e.g., what is a staircase) but also to build complex 3D models. Another interesting future research work could focus on a portable device at the intersection between the magnetic board and the 3D model, allowing OMIs to build quickly and easily a spatial model. A final extension of our work would be to use a touch sensitive technology [51] that allows to do without the PenFriend.

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REFERENCES

[1] 2016. Braille Literacy Statistics and How They Relate to Equality. https://brailleworks.com/braille-literacy-statistics/.

[2] 2021. *Quelques chiffres sur la déficience visuelle.* https://aveuglesdefrance.org/quelques-chiffres-sur-la-deficience-visuelle/

[3] Tânia Aciem and Marcos Mazzotta. 2013. Personal and social autonomy of visually impaired people who were assisted by rehabilitation services. *Revista Brasileira de Oftalmologia* 72 (08 2013), 261–267. https://doi.org/10.1590/S0034-72802013000400011

[4] Jérémy Albouys-Perrois, Jérémy Laviole, Carine Briant, and Anke M. Brock. 2018. Towards a Multisensory Augmented Reality Map for Blind and Low Vision People: A Participatory Design Approach. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3174203

[5] Mohammed Ibrahim Alhojailan and Mohammed Ibrahim. 2012. Thematic analysis: A critical review of its process and evaluation. *West east journal of social sciences* 1, 1 (2012), 39–47.

[6] Cecile Allaire. 2012. *Informer les personnes aveugles ou malvoyantes. Partage d'expériences.* Inpes, coll. Référentiels de communication en santé publique. https://www.santepubliquefrance.fr/docs/informer-les-personnes-aveugles-et-malvoyantes-partage-d-experiences

[7] AMI-télé. [n.d.]. *Les maquettes 3D de l'INLB.* Youtube. https://www.youtube.com/watch?v=BpXFPCqPyaY&ab_channel=AMI-t%C3%A9l%C3%A9

[8] Patrick Baudisch and Stefanie Mueller. 2016. Personal Fabrication: State of the Art and Future Research. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 936–939. https://doi.org/10.1145/2851581.2856664

[9] Cynthia L. Bennett, Abigale Stangl, Alexa F. Siu, and Joshua A. Miele. 2019. Making Nonvisually: Lessons from the Field *(ASSETS '19)*. Association for Computing Machinery, New York, NY, USA, 279–285. https://doi.org/10.1145/3308561.3355619

[10] Billie Louise Bentzen. 1972. Production and testing of an orientation and travel map for visually handicapped persons. *New Outlook for the Blind* 66, 8 (1972), 249–55.

[11] Sharon Bertsch, Bryan Pesta, Richard Wiscott, and Michael Mcdaniel. 2007. The generation effect: A meta-analytic review. *Memory & cognition* 35 (04 2007), 201–10. https://doi.org/10.3758/BF03193441

[12] Ann E. Bigelow. 1996. Blind and Sighted Children's Spatial Knowledge of Their Home Environments. *International Journal of Behavioral Development* 19, 4 (1996), 797–816. https://doi.org/10.1177/016502549601900407 arXiv:https://doi.org/10.1177/016502549601900407

[13] 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 arXiv:https://doi.org/10.1111/0033-0124.00191

[14] M Brambring and C. Weber. 1981. Taktile, verbale und motorische Informationen zur geographischen Orientierung Blinder [Tactile, verbal, and motor information for a geographic orientation of the blind]. *Zeitschrift für experimentelle und angewandte Psychologie* 28 (1981), 23—-37.

[15] Megen E. Brittell, Amy K. Lobben, and Megan M. Lawrence. 2018. Usability Evaluation of Tactile Map Symbols across Three Production Technologies. *Journal of Visual Impairment & Blindness* 112, 6 (2018), 745–758. https://doi.org/10.1177/0145482X1811200609 arXiv:https://doi.org/10.1177/0145482X1811200609

[16] 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 arXiv:https://doi.org/10.1080/07370024.2014.924412

[17] 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

[18] Emeline Brule, Gilles Bailly, Anke Brock, Frederic Valentin, Grégoire Denis, and Christophe Jouffrais. 2016. MapSense: Multi-Sensory Interactive Maps for Children Living with Visual Impairments. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 445–457. https://doi.org/10.1145/2858036.2858375

[19] Erin Buehler, Niara Comrie, Megan Hofmann, Samantha McDonald, and Amy Hurst. 2016. Investigating the Implications of 3D Printing in Special Education. *ACM Trans. Access. Comput.* 8, 3, Article 11 (mar 2016), 28 pages. https://doi.org/10.1145/2870640

[20] Erin Buehler, Shaun K. Kane, and Amy Hurst. 2014. ABC and 3D: Opportunities and obstacles to 3D printing in special education environments. In *ASSETS14 - Proceedings of the 16th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS14 - Proceedings of the 16th International ACM SIGACCESS Conference on Computers and Accessibility)*. Association for Computing Machinery, 107–114. https://doi.org/10.1145/2661334.2661365 16th International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS 2014 ; Conference date: 20-10-2014 Through 22-10-2014.

[21] Zaira Cattaneo, Tomaso Vecchi, Cesare Cornoldi, Irene Mammarella, Daniela Bonino, Emiliano Ricciardi, and Pietro Pietrini. 2008. Imagery and spatial processes in blindness and visual impairment. *Neuroscience & Biobehavioral Reviews* 32, 8 (2008), 1346–1360. https://doi.org/10.1016/j.neubiorev.2008.05.002 Special section: The European Workshop in Imagery and Cognition: Neurocognition and Visual Imagery.

[22] Erin C. Connors, Elizabeth R. Chrastil, Jaime Sánchez, and Lotfi B. Merabet. 2014. Virtual environments for the transfer of navigation skills in the blind: a comparison of directed instruction vs. video game based learning approaches. *Frontiers in Human Neuroscience* 8 (2014). https://doi.org/10.3389/fnhum.2014.00223

[23] Maitraye Das, Katya Borgos-Rodriguez, and Anne Marie Piper. 2020. Weaving by Touch: A Case Analysis of Accessible Making *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3313831.3376477

[24] Roger M. Downs and David Stea. 1973. *Cognitive Mapping and Spatial Behavior.* Chapter 1, 8–26. https://doi.org/10.4324/9780203789155

[25] 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 arXiv:https://doi.org/10.1177/0145482X9809200512

[26] M. A. Espinosa, Simon Ungar, Esperanza Ochaíta, Mark Blades, and Christopher P. Spencer. 1998. Comparing Methods for Introducing Blind and Visually Impaired People to Unfamiliar Urban Environments. *Journal of Environmental Psychology* 18 (1998), 277–287.

[27] Agebson Rocha Façanha, Ticianne Darin, Windson Viana, and Jaime Sánchez. 2020. O&M Indoor Virtual Environments for People Who Are Blind: A Systematic Literature Review. *ACM Trans. Access. Comput.* 13, 2, Article 9a (aug 2020), 42 pages. https://doi.org/10.1145/3395769

[28] Uttara Ghodke, Lena Yusim, Sowmya Somanath, and Peter Coppin. 2019. The Cross-Sensory Globe: Participatory Design of a 3D Audio-Tactile Globe Prototype for Blind and Low-Vision Users to Learn Geography. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 399–412. https://doi.org/10.1145/3322276.3323686

[29] Stéphanie Giraud, Anke M. Brock, Marc J.-M. Macé, and Christophe Jouffrais. 2017. Map Learning with a 3D Printed Interactive Small-Scale Model: Improvement of Space and Text Memorization in Visually Impaired Students. *Frontiers in Psychology* 8 (2017). https://doi.org/10.3389/fpsyg.2017.00930

[30] Stéphanie Giraud and Christophe Jouffrais. 2016. Empowering Low-Vision Rehabilitation Professionals with "Do-It-Yourself" Methods. *LNCS* 9759, 61–68. https://doi.org/10.1007/978-3-319-41267-2_9

[31] Stéphanie Giraud, Philippe Truillet, Véronique Gaildrat, and Christophe Jouffrais. 2017. DIY Prototyping of Teaching Materials for Visually Impaired Children: Usage and Satisfaction of Professionals. https://doi.org/10.1007/978-3-319-58706-6_42

[32] 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

[33] Jaume Gual, Marina Puyuelo, and Joaquim Lloveras. 2015. The effect of volumetric (3D) tactile symbols within inclusive tactile maps. *Applied Ergonomics* 48 (2015), 1–10. https://doi.org/10.1016/j.apergo.2014.10.018

[34] Yvette Hatwell. 2006. Appréhender l'espace pour un enfant aveugle. *Enfances & Psy* 33 (11 2006). https://doi.org/10.3917/ep.033.0069

[35] Leona Holloway, Matthew Butler, and Kim Marriott. 2022. 3D Printed Street Crossings: Supporting Orientation and Mobility Training with People Who Are Blind or Have Low Vision *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 415, 16 pages. https://doi.org/10.1145/3491102.3502072

[36] Leona Holloway, Kim Marriott, and Matthew Butler. 2018. Accessible Maps for the Blind: Comparing 3D Printed Models with Tactile Graphics. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173772

[37] Andreas Hub, Joachim Diepstraten, and Thomas Ertl. 2003. Design and Development of an Indoor Navigation and Object Identification System for the Blind. *SIGACCESS Access. Comput.* 77–78 (sep 2003), 147–152. https://doi.org/10.1145/1029014.1028657

[38] 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

[39] R. Dan Jacobson. 1998. Navigating maps with little or no sight: An audio-tactile approach. In *Content Visualization and Intermedia Representations (CVIR'98)*. https://aclanthology.org/W98-0214

[40] Rob Kitchin and Dan Jacobson. 1997. Techniques to Collect and Analyze the Cognitive Map Knowledge of Persons with Visual Impairment Or Blindness: Issues of Validity. *Journal of Visual Impairment and Blindness* 91 (07 1997). https://doi.org/10.1177/0145482X9709100405

[41] O. Lahav and D. Mioduser. 2008. Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. *International Journal of Human-Computer Studies* 66, 1 (2008), 23–35. https://doi.org/10.1016/j.ijhcs.2007.08.001

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

[43] Carine Lallemand and Vincent Koenig. 2017. "How Could an Intranet be Like a Friend to Me?" - Why Standardized UX Scales Don't Always Fit. https://doi.org/10.1145/3121283.3121288

[44] Megan M. Lawrence and Amy K. Lobben. 2011. The Design of Tactile Thematic Symbols. *Journal of Visual Impairment & Blindness* 105, 10 (2011), 681–691. https://doi.org/10.1177/0145482X1110501014 arXiv:https://doi.org/10.1177/0145482X1110501014

[45] Barbara Leporini, Valentina Rossetti, Francesco Furfari, Susanna Pelagatti, and Andrea Quarta. 2020. Design Guidelines for an Interactive 3D Model as a Supporting Tool for Exploring a Cultural Site by Visually Impaired and Sighted People. *ACM Trans. Access. Comput.* 13, 3, Article 9 (aug 2020), 39 pages. https://doi.org/10.1145/3399679

[46] Luis Fernando Milan and Gabriela Celani. 2007. Tactile scale models: Three-dimensional info-graphics for space orientation of the blind and visually impaired. (01 2007), 801–805.

[47] S. Millar. 1994. *Understanding and Representing Space: Theory and Evidence from Studies with Blind and Sighted Children.* Clarendon Press. https://books.google.fr/books?id=6nhoi8Hzuo4C

[48] Susanna Millar. 1995. Understanding and representing spatial information. *British Journal of Visual Impairment* 13, 1 (1995), 8–11. https://doi.org/10.1177/026461969501300102 arXiv:https://doi.org/10.1177/026461969501300102

[49] Dominika Palivcová, Miroslav Macík, and Zdeněk Míkovec. 2020. Interactive Tactile Map as a Tool for Building Spatial Knowledge of Visually Impaired Older Adults. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3334480.3382912

[50] 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)* 1, 141–146.

[51] Brice Parilusyan, Marc Teyssier, Valentin Martinez-Missir, Clément Duhart, and Marcos Serrano. 2022. Sensurfaces: A Novel Approach for Embedded Touch Sensing on Everyday Surfaces. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 2, Article 67 (jul 2022), 19 pages. https://doi.org/10.1145/3534616

[52] R. Passini, A. Dupré, and C. Langlois. 1986. Spatial Mobility of the Visually Handicapped Active Person: A Descriptive Study. *Journal of Visual Impairment & Blindness* 80, 8 (1986), 904–907. https://doi.org/10.1177/0145482X8608000809 arXiv:https://doi.org/10.1177/0145482X8608000809

[53] Lorenzo Picinali, Amandine Afonso, Michel Denis, and Brian F.G. Katz. 2014. Exploration of architectural spaces by blind people using auditory virtual reality for the construction of spatial knowledge. *International Journal of Human-Computer Studies* 72, 4 (2014), 393–407. https://doi.org/10.1016/j.ijhcs.2013.12.008

[54] Andreas Reichinger, Moritz Neumüller, Florian Rist, Stefan Maierhofer, and Werner Purgathofer. 2012. Computer-Aided Design of Tactile Models. In *Computers Helping People with Special Needs*, Klaus Miesenberger, Arthur Karshmer, Petr Penaz, and Wolfgang Zagler (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 497–504.

[55] Jaime Sánchez, Matías Espinoza, Marcia de Borba Campos, and Lotfi B. Merabet. 2013. Enhancing Orientation and Mobility Skills in Learners Who Are Blind through Video Gaming *(C&C '13)*. Association for Computing Machinery, New York, NY, USA, 353–356. https://doi.org/10.1145/2466627.2466673

[56] Saquib Sarwar and David Wilson. 2022. Systematic Literature Review on Making and Accessibility. In *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility* (Athens, Greece) *(ASSETS '22)*. Association for Computing Machinery, New York, NY, USA, Article 84, 5 pages. https://doi.org/10.1145/3517428.3550377

[57] Brandon Taylor, Anind Dey, Dan Siewiorek, and Asim Smailagic. 2016. Customizable 3D Printed Tactile Maps as Interactive Overlays. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility* (Reno, Nevada, USA) *(ASSETS '16)*. Association for Computing Machinery, New York, NY, USA, 71–79. https://doi.org/10.1145/2982142.2982167

[58] Simon Ungar. 2018. *Cognitive mapping without visual experience.* 221–248. https://doi.org/10.4324/9781315812281-13

[59] Simon Ungar, Mark Blades, and Christopher Spencer. 1993. The role of tactile maps in mobility training. *British Journal of Visual Impairment* 11, 2 (1993), 59–61. https://doi.org/10.1177/026461969301100205 arXiv:https://doi.org/10.1177/026461969301100205

[60] Bert Vandenberghe, Kathrin Gerling, Luc Geurts, and Vero Vanden Abeele. 2022. Maker Technology and the Promise of Empowerment in a Flemish School for Disabled Children. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 546, 18 pages. https://doi.org/10.1145/3491102.3501853

[61] Viswanath Venkatesh, Michael G. Morris, Gordon B. Davis, and Fred D. Davis. 2003. User Acceptance of Information Technology: Toward a Unified View. *MIS Quarterly* 27, 3 (2003), 425–478. http://www.jstor.org/stable/30036540

[62] Jakub Wabiński, Albina Mościcka, 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 arXiv:https://doi.org/10.1080/00087041.2022.2097760

[63] Chih-Fu Wu, Hsiang-Ping Wu, Yung-Hsiang Tu, I-Ting Yeh, and Chin-Te Chang. 2022. A Study on the Design Procedure of Three-Dimensional Printable Tactile Graphics for Individuals With Visual Impairments. *Journal of Visual Impairment & Blindness* 116, 4 (2022), 507–516. https://doi.org/10.1177/0145482X221122754 arXiv:https://doi.org/10.1177/0145482X221122754