A Haptic-audio Human-Computer Interface

Acquisition of Indoor Spatial Knowledge by Visually Impaired People

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Abstract

For the visually impaired it is important to acquire knowledge about environments in advance. Haptic-audio interfaces have been proven as appropriate to represent certain types of spatial knowledge in a non-visual manner. This dissertation elaborates on a haptic-audio interface that supports non-visual spatial knowledge acquisition of indoor environments.

Three representational layers relevant for acquisition of indoor spatial knowledge using the haptic-audio interface are defined in the following: (a) knowledge concerning room access and the layout of individual rooms and whole flats, (b) knowledge about the location of functional facilities (such as, windows, radiators, and power-outlets), and (c) knowledge regarding the position of furniture. In correspondence, three research questions were investigated, namely (i) how to represent boundaries among areas and access to areas, (ii) how to represent linear spatial overlapping aroused by the presence of functional facilities, and (iii) how to represent 2-D spatial overlapping aroused by furniture pieces in rooms. Based on these considerations, a haptic-audio interface is implemented as non-visual floor plans that can be perceived with the PHANToM virtual force feedback device.

In order to discuss the research questions mentioned above, a user-centered research methodology is employed in this dissertation. User behavior was observed and evaluated with help of usability studies. Users requirements and expectations were investigated through focus group studies. Based on empirical analyses of the three representation layers of the haptic-audio interface, this dissertation represents room access and layout of an indoor environment through virtual haptic models. Linear spatial overlaps are represented with the support of sonification. Further more, a two-phase haptic-audio exploration strategy is proposed to acquire spatial knowledge involving 2-D spatial overlapping: In the first phase, the floor plan on display is unfurnished and the functional facilities are sonified. Then in the second phase, virtualization of furniture pieces is further displayed.

The empirical results show that spatial knowledge of room-access and layouts of indoor environments can be acquired by visually impaired people through exploration in haptic-audio virtual environment. Plausibility of acquiring spatial knowledge involving linear overlapping and 2-D overlapping is also presented.

Zusammenfassung

Für sehbehinderte Menschen ist es wichtig, vorzeitig räumliches Wissen über Umgebungen zu erwerben. Haptisch-akustische Schnittstellen haben sich für die nichtvisuelle Darstellung gewisser Arten räumlichen Wissens als geeignet erwiesen. Diese Dissertation stellt eine haptisch-akustische Schnittstelle vor, welche die Aneignung nichtvisuellen räumlichen Wissens über Innenumgebungen unterstützt.

Drei Präsentationsebenen für den Erwerb räumlichen Wissens mit Hilfe der haptisch-akustischen Schnittstelle werden definiert: (a) Wissen über die Zugänglichkeit sowie Lage und Anordnung von Räumen und ganzen Wohnungen, (b) Wissen über die Lage funktionaler Einrichtungen (wie Fenster, Heizkörper und Steckdosen) und (c) Wissen über die Lage von Möbelstücken. Dementsprechend werden drei Forschungsfragen gestellt, nämlich nach der geeignetsten Darstellung (i) von Grenzen und Zugänglichkeit von Gebieten, (ii) von linearer räumlicher Überlappung aufgrund der Anwesenheit mehrerer funktionaler Einrichtungen und (iii) von 2D-Überlappungen aufgrund der Anwesenheit mehrerer Möbelstücke. Eine entsprechende haptisch-akustische Schnittstelle für nichtvisuelle Grundrisse wird implementiert, welche mit dem PHANTOM Force-Feedback-Gerät benutzt werden kann.

Um die oben gestellten Forschungsfragen zu bearbeiten, wird in dieser Arbeit eine nutzerzentrierte Methodologie verwendet. Das Nutzerverhalten wurde durch Usability-Studien beobachtet und ausgewertet. Nutzeranforderungen und -erwartungen wurden durch Fokusgruppenstudien untersucht. Aufgrund von empirischen Analysen der drei Präsentationsebenen der haptisch-akustischen Schnittstelle werden in dieser Dissertation die Zugänglichkeits- und Lageinformationen von Innenumgebungen durch virtuelle haptische Modelle repräsentiert. Die lineare räumliche Überlappung wird mit Hilfe von Sonifizierung dargestellt. Um die Erfassung von 2D-Überlappungen zu unterstützen, wird eine zweiphasige haptisch-akustische Explorationsstrategie vorgeschlagen: In der ersten Phase wird nur ein Grundriss ohne Möbel, jedoch mit funktionalen Einrichtungen präsentiert. In der zweiten Phase kommen dann Repräsentationen von Möbelstücken hinzu.

Die empirischen Ergebnisse zeigen, dass sehbehinderte Menschen durch Exploration einer virtuellen haptisch-akustischen Umgebung räumliches Wissen über Raumzugänglichkeit, Lage und Anordnung in Innenumgebungen erwerben können. Ebenfalls wird es präsentiert, dass Nutzer räumliches Wissen über lineare und 2D-Überlappungen erwerben konnen.

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Chapter 1

Haptic-audio virtual environments for visually impaired people

1.1 Motivation

The last two decades have witnessed computer science emerging and and playing an essential role in reinforcing pedagogics for people with special needs or limitations, among others, for people who are blind or visually impaired[1] Since the 1990s, barrier-free human-computer interaction and web accessibility have become big issue for modern computer science. Consequently, the accessibility of information and communications has been extended from pure text to graphics[2]. Graphics are heavily used in human-computer interaction scenarios, and more importantly, they are usually functional visual external representations of specific knowledge that could be complicated, frustrating, or tedious when described or explained with pure text. Among all the types of existing graphics, computer scientists seem to be particularly attracted by maps, commonly used by humans for borth representing and requesting spatial knowledge.

Making more graphics accessible to the visually-impaired effectively meets the legal and social concerns for people with special needs. According to the World

[1] Blind people and visually impaired people differ in many perspectives. However, both groups share common ground regarding human-computer interaction. In this dissertation, the term "visually impaired people" refers to both the blind people and the visually impaired. In specific cases, the two groups are discussed explicitly.

[2] In this dissertation, the word "graphics" refers to those which contribute substantial information, like mathematical diagrams, engineering drawings, and especially maps of various scales. Drawings, photographs, and other works of art graphics are not relevant and not referred to.

Health Organization (WHO), the number of people with vision problems has increased from 126.6 million in 2003 to 285 million in 2012. So it makes a lot sense to pay attention to this group's demand of information access. And more generally, not only those, who are currently visually impaired people, but also for everyone else. People all grow old. Gradually, it will become more and more challenging to have good eyesight. Therefore, elderly people also benefit from the accessibility support. The Convention on the Rights of Persons with Disabilities published by the UN (*Convention on the Rights of Persons with Disabilities*, 2006) focuses on accessibility in Article 9, trying to promote access to information for visually impaired people. The European Disability Strategy also claims accessibility as its first major area of action until 2020 (*European Disability Strategy 2010-2020*, 2010). There are also a large number of countries that have released individual substantial legislations that directly address access to information for visually impaired people, especially after the famous legal case in Sydney (*Maguire v. SOCOG*, 2000). It was the first successful case under the Disability Discrimination Act (1992), as the Sydney Organizing Committee of the Olympic Games (SOCOG) had failed to make their official website adequately accessible to visually impaired people. Therefore, making a wide rage of content produced by computers accessible to visually impaired people means making convenient computer services more accessible to them, as referred to in the social and legal concerns mentioned above.

With respect to daily mobility and orientation tasks, visual input is one of the most important resources of spatial knowledge of external environments for human individuals. When the sense of vision is absent, exploring and interacting with a novel environment by using one's own limbs is also a commonly used strategy. But the range of limbs has its solid limits, which results in a tedious task when getting familiar with environments that are large or complex. Furthermore, different from outdoor environment, blind roads are hardly available inside buildings, which makes familiarizing with a novel indoor environments even more challenging for visually impaired people. That is why appropriate non-visual spatial representations for visually-impaired people are important.

In this dissertation, a human-computer interface as a haptic-audio floor plan is discussed. This interface can help visually impaired people to acquire spatial knowledge of novel indoor environments. Virtual haptic force feedback is used to support wall-following strategies in novel environment explorations. Sonification is employed to represent wall-embedded functional facilities (windows, radiators, and power-outlets) of indoor environments. Furthermore, non-visually accessible furniture pieces are also supported. This human-computer-interface is evaluated through empirical studies with both sighted and visually impaired participants.

1.2 Haptic-audio virtualization for non-visual spatial knowledge acquisition

Virtualization is a traditional approach towards visual external representations in a non-physical manner. By means of perceiving and understanding visual external representation of physical environments, human beings are able to acquire spatial knowledge and establish a spatial mental model.

When the sense of vision is absent, external representations should be realized so that they can be perceived through other sensory modalities of human beings, which is a pre-condition of further knowledge acquisition tasks (Card, 1996). Both the haptic and the audio channel are frequently employed as alternative perceptual channels for visually impaired people.

Physical external representations realized with haptic and audio stimuli for visually impaired people are widely produced and used. But, in comparison, more advantages are provided by virtually realized haptic-audio representations. In virtual reality, audio stimuli are more flexibly integrated by use of haptic representations. For users, it is more efficient to perceive and understand virtual haptic representations with help of virtual haptic force feedback devices, and producing virtual haptic representations is less demanding than physical haptic representations regarding time and costs (Rowell & Ungar, 2003a). Therefore, haptic-audio external representations in virtual environments are employed in this dissertation and referred to as *haptic-audio virtualization*.

1.2.1 Reality and virtual reality of indoor environments

With the development of modern computer technologies such as CAD tools, the quality and accuracy of floor plans is more advanced than ever. Numerous designers, developers, and users agree that the more details a visual representation contains, the better it is. Based on this idea, architects and building designers have started to use high quality 3-D virtual floor plans (Yin et al., 2009). And there are also more and more 3-D virtual floor plan applications for consumers and users to deal with individual designing, such as the IKEA Home Planner series and other commercial products. However, when the sense of vision is absent, in order to acquire spatial knowledge, the sense of touch and auditory are in charge of perceiving graphical and spatial representations. Due to the local and sequential nature of haptic perception (Loomis et al., 1991), and the fact that speech, just like audio assistance, requires time to convey substantial contents, large amounts of detailed information can dramatically increase the time consumption and mental efforts by users (Rowell & Ungar, 2003b). According to the results of pioneer researches, when a non-visual representation conveys information that exceeds a manageable amount for visually impaired people, only very coarse qualitative information can be extracted from a virtual floor plan with very high granularity and complexity, resulting inefficient. For example, a strictly reality-oriented 3-D virtual indoor environment for visually impaired people was designed and implemented by Huang (2010). It was a vivid representation of a realistic two-story indoor environment, in which a door, an escalator, a desk, and a sofa were to be found by experiment participants. However, after time-consuming explorations of about an hour, only 60% of the participants were able to identify all the objects. Similar cases can be found in realistic representations of outdoor scenarios, too. To support the way-finding abilities of the visually impaired, Magnusson & Rassmus-Gröhn (2005), for instance, implemented a virtual environment of a junction containing 484 static objects and even dynamic entities, such as cars and bicycles. (The dynamic cars and bicycles were obeying the traffic rules.) With the mentioned complex virtual environment, participants did not find it very challenging to find the nearby bus-stop just beyond the street-crossing. However, for mere way-finding tasks, the complexity of the virtual environment was apparently over done. The authors claimed that such detailed virtual environments were supposed to be more suitable for simulation and training purposes, rather for spatial knowledge acquisition purposes.

Therefore, it makes sense to determine type and manner of representing knowledge. Regarding spatial knowledge representation for visually impaired people, the richness of detailed information addressed by a specific representation should be balanced against its legibility and efficiency.

1.2.2 The spatial mental model of visually impaired people

The spatial mental model is referred to as the internal spatial representations of environmental space. The required spatial knowledge can be acquired through direct perception, locomotion, or external representations such as maps and floor plans (Beck & Wood, 1976; Montello, 1993). Spatial mental models for environments, as elaborated by Golledge (1999) and Ungar (2000), can be divided into two types: route-like spatial mental models and survey-like spatial mental models. In floor plan scenarios, route-like spatial mental models support the route-finding tasks in an egocentric manner, whereas survey-like spatial mental models make it possible to deal with planning orientation and mobility in an allocentric manner. In spite of the findings testifying that visually impaired people have a preference for replying to egocentric route-like spatial mental models (Millar, 1994), the hypothesis that the visually impaired can establish both route-like and survey-like representations is supported by empirical evidence (Noordzij et al., 2006; Corazzini et al., 2010).

As reviewed by Lohmann (2013) and given the appropriate means of spatial knowledge acquisition, visually impaired people can construct spatial mental models in a similar way to sighted people. Therefore, external representations of environmental space based on suitable sensory and representational multi-modalities play a critical role in spatial knowledge acquisition. Furthermore, through an empirical study that compares spatial knowledge acquired from locomotion in a physical environment to non-visual maps, Espinosa et al. (1998) showed that visually impaired people can get familiar with novel environments efficiently using non-visual maps. Non-visual maps can also prevent visually impaired people from being exposed in novel environments too early. Therefore, they can benefit from non-visual external representations by acquiring spatial knowledge before their first visit in physical novel environments.

1.2.3 Physical and virtual non-visual graphics

As reviewed by Picinali et al. (2014), sufficient information for constructing mental spatial models of novel environments can be acquired from external non-visual spatial representations. Usually such external representations can be divided into two major types: namely haptic tactile graphics and virtual haptic models.

Haptic-audio vs. tactile-audio — term selection

Before discussing the types of non-visual external spatial knowledge representations, it makes sense to clarify the terminology. Both the root words *haptic* and *tactile* have been frequently employed in researches and work when the sense of touch is involved. Sometimes, the selected words are consistent with the work they refer to, but sometimes, they are not.

Coming from a background of human-computer interaction, I would decompose this problem within the somatosensory system of human beings. In medicine, the sense of touch can also be referred to as the *somatic senses* or *somesthetic senses*. Somesthesis covers the concepts of touch, proprioception, as well as haptic perception (Augustine, 2008) and the domain in which the terms *tactile* and *haptic* apply can be distinguished by different sensory receptors involved in stimuli detection and perception. A somatosensory system detects stimuli by mechanoreceptors for tactile sensation, in which the mechanical pressure, distortion and deformation of skin play an important role. Therefore, the term *tactile* should be used to describe the sense of touch that belongs to the classic *Five Senses*. Whereas the term *haptic* should safely describe a combination of somatosensory and proprioception which cannot be completely covered by the classic *Five Senses* (Streri & Spelke, 1988)[3], as here, the relative position of muscles and joints, and the strength applied in movement is detected by stretch receptors and joint-supporting ligaments (Anderson et al., 2005).

So there is nothing wrong with employing *virtual haptics* as the terminology for virtual force feedback technology involving interaction with the entire arm of its users. As a matter of fact, the users' input while operating the Omni joystick is mainly perceived as position and movement of muscles and joints of the forearm, while the extension and deformation of skin aroused incidentally does not contribute substantial information to communications. Therefore, the virtual human-computer interface referred to in this dissertation should be better be described as *haptic-haptic floor plans* rather than substituting it through *tactile*. On the other hand, traditional paper-based embossed external representations, such as braille and dotted graphics should be described as *tactile* displays.

Physical tactile graphics

One of the widely followed golden rules for designing and producing tactile graphics for visually impaired people is to *omit things* (Edman, 1992), which means identifying unessential information and essential information so as to the make the latter more accessible to visually impaired readers. In order to follow the principle, only the most important elements should be represented. In a floor plan scenario, it should be the layout of the represented indoor environment. The layout is actually defined by the walls and doors in the corresponding indoor environment.

In a physical non-visual representation, graphical elements are usually implemented as dots, lines, and symbols with a specific elevation, so as to be perceivable in a sequential manner by the fingertips of visually impaired readers (Jehoel et al., 2009; Koch, 2012). Therefore, such tactile graphics are usually designed in a 2.5-dimensional way. As they differ from traditional 2-D visual graphics, tactile graphics use elevation for all graphical elements. On the other hand, the height of the elevation assigned to these dots, lines, and symbols does not map the physical height of represented objects in realistic world in the same way as real 3-D representations. Nowadays, such 2.5-D tactile graphics are often produced through thermoform and microcapsule technology (Rowell & Ungar, 2003a). The size of tactile graphics is suggested to be smaller than A3. When a large amount of information has to be represented, tactile graphics are designed as atlas (a series of maps/graphics) or as multiple layers, so as to keep the amount of information con-

[3]Human senses that enable the detection of stimuli beyond the scope covered by the classic *Five Senses* are thermoception (Bliss, 1982), proprioception (Robles-De-La-Torre, 2006), nociception (Fulbright et al., 2001), equilibrioception (Russell & Cohn, 2012), chronoception (Rao et al., 2001) and interoception (Craig, 2003).

veyed in each partition under a manageable amount for visually impaired readers (Rowell & Ungar, 2003b).

The possibility of having information expressed audibly addresses one of the most challenging issues in designing physical tactile graphics and was reported to be the manipulation of textual contents (Rowell & Ungar, 2003b). Braille text in tactile graphics is important for readers in order to understand the knowledge represented. However, it should be designed in a sensible way. For example, if the size of Braille text is too large, although it may reach very good legibility, the continuity of sequential perception of other graphical elements can be damaged. And it is also worth noting that not all visually impaired people are able to read Braille text. When textual information is given via the audio channel, graphic readers can perceive and interpret different information from both haptic and audio channels concurrently.

The refreshable haptic pegboard is a milestone for physical tactile displays. Coordinate-based haptic effects have been realized by bundling a number of haptic actuators in a matrix way. It is possible to render haptic effects on different positions of a screen or a touch panel, which makes it possible to represent mainly textual contents and sometimes very simple shapes and symbols(Hayward & Cruz-Hernández, 2000; Kajimoto et al., 2001; Maucher et al., 2001). Later, following this concept, non-visual computer output devices, such as the refreshable Braille display, utilizing piezoelectric actuator technology were implemented and made available (see Figure 1.1) (Völkel et al., 2008; Zeng & Weber, 2010). Other technologies, such as electrothermally controlled actuators (Lee & Lucyszyn, 2005) and pneumatically driven actuators (Yobas et al., 2003) and so on, were also investigated.

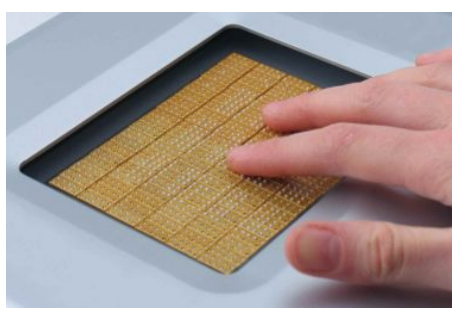


Figure 1.1: Small-scale prototype of a refreshable tactile pegboard (Völkel et al., 2008).

Virtual haptic interfaces

Aside from physical tactile graphics, there are also virtual non-visual graphics available, covering the scope of various charts, diagrams, maps, etc (Panëels & Roberts, 2010). Normally, virtual tactile graphics consist of virtual models that can be perceived through operating virtual force feedback devices and audio input. They provide readers with relevant information to support or improve knowledge acquisition.

One of the core features of virtual haptics technologies currently targeted at visually impaired people is more like a natural manipulation of 3-D objects. The current generation of haptics no longer relies only on devices with an actuators matrix, but on reverse mechanic arms or joysticks to render virtual haptic force feedback, supporting vivid perception and interaction of almost all kinds of virtual objects with hardly any constraints regarding shapes and stiffness of objects. One of the most popular commercial 3-D virtual haptic products is the PHANToM system. The device named PHANToM Omni has gained a large market presence with reasonable prices and satisfying performances (see Figure 1.2). A more important feature of the latest virtual haptics technologies is the integration of different sensory modalities, which makes the representation of spatial knowledge through virtual haptics more intuitive and more efficient. Haptic-audio multimodal human-computer-interaction is one of the most widely accepted and investigated approaches in rehabilitation (G. Song & Guo, 2006; Adamovich et al., 2009; Xu et al., 2010), education (W. Yu et al., 2003; Minogue & Jones, 2006; Richard et al., 2006; Mikropoulos & Natsis, 2011) and surgical training (Feygin et al., 2002; Basdogan et al., 2004; Meijden & Schijven, 2009; Deshpande et al., 2012), especially where scenarios involving the acquisition of spatial knowledge of visually impaired users are concerned (Magnusson et al., 2002; Lahav & Mioduser, 2008; Huang, 2010; J. Yu & Habel, 2012). Differing from refreshable tactile displays, the latest virtual haptics enable users to intuitively communicate three dimensional spatial knowledge to users.

Virtual haptic technologies provide virtual representative models with collision properties that act in a physically intuitive manner when they are touched by users through a force feedback mechanical human-computer interface (Ruspini, 2003). When a virtual haptic interaction point is in contact with a virtual model, corresponding haptic features can be simulated and then perceived by the user's hand that holds the mechanic arm or the stylus attached to the force feedback device (Rassmus-Gröhn, 2006). Throughout this dissertation, the employed force feedback device is called PHANToM OMNI (see Figure 1.2). In comparison to other hardware available on the market, OMNI has a very good price/performance ratio. With nominal position resolutions of 0.055 mm, a very smooth virtual

Figure 1.2: Phantom OMNI haptic device, manufactured by Sensable Technologies.

kinesthetic display can be supported. The force feedback output can range from 0 to 3.3 N. Additionally, it has minimum space requirements, as it is only 168 mm wide and 203 mm long. Furthermore, during the haptic exploration of a virtual model, it is also possible for users to receive audio stimuli implemented by graphic producers. These facts make OMNI an appropriate solution for non-visual virtual tactile graphics on desktops.

1.2.4 Understanding virtual haptic graphics

Hybrid representations in non-visual haptic-audio interfaces

As elaborated by Habel (2003), external representations can be divided into propositional representations and analog representations, which is in line with the definitions proposed by Palmer (1978).

Analog knowledge provides users with information using granularity levels, representing geometrical and quantitative spatial properties of objects on floor plans, such as position, shape, and dimensions of objects, which make it possible to establish more precise presentations of the floor plans. In virtual haptic floor plans, analog knowledge is perceived by users through haptic exploration. The position of the entities can be perceived by users according to the virtual force feedback applied to the stylus when the haptic interaction point establishes contact with the corresponding entity. Geometrical dimensions of objects are capsulized in the haptic movements made by users in a virtual environment. The hypothesis suggests that users can interpret analog properties of virtual objects (e.g. position, length, and width) by integrating the direction, velocity, and time duration of their haptic movements.

Propositional knowledge, on the other hand, covers the basic properties of the virtual haptic environments, and the unique or essential properties of objects in floor plans which are necessary to identify objects (or types of objects). It is not very challenging to represent and haptically perceive certain propositional knowledge, such as the floor ground, the walls, the doors, and the furniture pieces, while other propositional knowledge is represented more efficiently with audio assistance. When information regarding the room names of different areas defined by the internal walls and the names of each piece of furniture on the floor plans is represented haptcially, it has to be represented using Braille. This means that the haptic exploration of floor plans has to be interrupted. If this information is communicated by audio assistance, users are required to receive the extra audio information and perform haptic exploration at the same time.

Representational multi-modality in virtual haptics

As reviewed by Bernsen (1994), humans can perceive a large variety of stimuli through haptic perception. However, the nature of dynamic interaction is one solid property of haptic perception. Human beings can distinguish objects depending on differences in roughness, vibration, localization, and passive movement of stimuli (Grünwald, 2008). Therefore, this dissertation suggests to employ these modalities in virtual haptic stimuli as non-visual representations on floor plans. For the very first implementation, only the most elementary components of floor plans are represented, namely walls as divisions and identifiers of rooms and areas, and doors as access to further defined individual areas.

Audio assistance

In addition to haptic modality, audio stimuli also contribute to non-visual hybrid representations. Audio assistance employed in modern multi-modal human-computer interfaces can be divided into two sections, namely verbal assistance and sonification. In scenarios of non-visual graphical representations, limits of expressing knowledge through verbal assistance are exposed. Usually, it is challenging to represent simple graphical concepts with a short text (Barker & Manji, 1989). Furthermore, in order to make sense from textual stimuli, users have to comprehend words and expressions from the beginning to the end of a piece of textual message so as to understand the information expressed (Brewster, 1994). On the other hand, it is challenging to update the production and perception of textual representations according to the real-time dynamic exploration on virtual haptic floor plans.

In comparison, information communicated by sonification can be protocolized in advance. Then during haptic exploration, users can immediately comprehend the information expressed when sonification is fired out. Invoking and terminating sonification can also be manipulated by haptic exploration of users following a rule-based algorithm. Therefore, the virtual haptic floor plans discussed in this dissertation employ verbal assistance only to inform users about propositional knowledge, such as name and function of rooms or objects, whereas analog properties, such as shapes and sizes of individual rooms and the entire layout of an apartment, are represented by virtual haptic force feedback. Analog properties of extended objects, such as position and width of windows in walls, are represented by sonification, which is non-speech audio (Nees & Walker, 2009).

Now that both verbal assistance and sonificaiton are employed in haptic floor plans, the question is whether these two different types of audio stimuli interfere with each other. Fortunately, as reviewed by Barrass & Kramer (1999), visually impaired people are more skilled in manipulating acoustic stimuli than sighted people, and they can filter useful sounds out of those that are not. Researchers and scientists have also proven that human beings are able to transform concurrent audio input into separate sound streams depending on several particular properties (e.g. frequency, rhythm, timbre, and the spatial origin of the sound) (Bernsen, 1994; H. J. Song et al., 2007; Shamma et al., 2011). This implies that it is plausible for users to receive concurrent verbal assistance and sonification and feasible to receive different types of sonification at the same time.

Among all the optional properties of sonification stimuli, the differences in frequency and rhythm are ideal to make sonification distinguishable, since human beings are significantly sensitive to changes in frequencies. The just-noticeable difference (JND) for frequencies of harmonic waves is as small as 6‰, and the rate of concurrent harmonic wave stimuli is even smaller (Benesty et al., 2008). Besides, the rhythm changes are very good at shifting and grasping the attention of listeners, normally with 2-10‰ of the value of JND (Thomas, 2007).

In indoor environment scenarios, the complexity of both propositional representations (e.g. all the room types) and analog representations (e.g. size and position of wall-embedded functional facilities, such as windows, radiators, and power-outlets) are limited, making the hybrid representations of these two types (as reviewed by Habel (2003)) easy to learn and handle by using a division-of-labor protocol where verbal assistance is employed in propositional representations while sonification is used in analog representation.

Yet the plausibility of using sonification to support the acquisition of analog knowledge involving spatial-overlapping during haptic exploration has not been explored, as investigated in the empirical studies in Chapter 3 of this dissertation.

1.3 Representation layers of floor plans for indoor environments

As reviewed in Section 1.2.3, both 3-D and 2.5-D virtual haptic representations exist. In 3-D haptic-audio virtualization, it is feasible to represent indoor environments with finely-grained details on the internal surface of every wall section. Consequently, in order to get familiar with a novel indoor environment, users have to explore at least five surfaces (four vertical walls and the horizontal ground floor, since exploring the ceiling is not supposed to be critical for mobility and orientation purposes to visually impaired people). In comparison, 2.5-D haptic-audio virtualization of indoor environments suggest a strategy for users, advising to explore only one surface to acquire spatial knowledge, such as region and shape, availability of functional facility, and furniture configuration, which is supposed to save time and effort for visually impaired users considerably. Therefore, in order to make use of this advantage, 2.5-D haptic-audio virtualization has been employed in this dissertation.

It is normal that different purposes and subjective requirements exist. Consequently, they should also be derived from various user expectations and added to the substantial information represented by an external representation. Some people might be interested in the global layout of an indoor environment in order to locate one or more specific rooms. Other individuals may need to know what kind of functional facilities are available in specific rooms in order to determine the functions of rooms. It is also likely that some people find it important to be informed about the detailed furniture configuration of the rooms. Depending on the type and amount of information the virtual haptic interface covers, as well as the complexity of the spatial knowledge represented, three representation layers of virtual haptic floor plans are defined in this dissertation. In Layer I, spatial knowledge of regions and shapes of indoor environments can be acquired. Layer II supports knowledge acquisition of spatial constellations involving linear overlapping addressing the representation of wall-embedded facilities of indoor environments, such as windows, radiators, and power-outlets. Based on Layer I and Layer II, Layer III offers a solutions to represent 2-D overlapping between the regions and objects inside them.

1.3.1 Layer I: Regions and shapes of indoor environments

Dealing with way-finding tasks in novel indoor environments is one of the most common and basic challenges for visually impaired people in daily life. Visually impaired people may have to search for a specific room in a clinic or in a government building, etc. for the first time. In this scenario, the knowledge of regions and shapes of the environment attracts the greatest interest of users. As summarized by Ishikawa et al. (2011), there are five major variables that can disclose the variations of floor plans to humans in terms of perception and cognition:

1. *The number of the rooms*: the number of different areas depicted on the floor plan, including all the rooms and the hallway.
2. *The layout of an environment* (access to the rooms):
   i. Relative positions of hallways in apartments.
   ii. Relative positions of every single room in relation to the hallway and the other rooms.
   iii. Access to every single room.
3. *The global shape of an environment*: the global overall shape, of the entire floor plan. This sketch should not only reveal that the global shape of the floor plan is either rectangular or L-shaped, but it should also show consistence in the scaling dimensions (e.g. whether a rectangle is longer in the vertical dimension or in the horizontal dimension), otherwise the global shape of the floor plan is regarded as not correctly sketched. A sketch can get one point for showing the global shape of an apartment correctly
4. *Local shapes of every single room*: the local shape of every single area, including rooms and the hallway. The detailed rating principle is the same as for global shapes.
5. *Position of the doors*
   i. The proportional position of the door with respect to the section of wall it is embedded in.
   ii. Every wall section can be divided into three parts: left, middle, and right, or upper, middle, and bottom. If the door in the sketch is in the same part of the wall section as the door on the floor plan, it is regarded as correct.
   iii. Opposite doors on two opposite walls. If a pair of opposite doors are not in the correct part of the embedded wall, but is still opposite to the other door as displayed in the original floor plan, both doors will lose points.

Spatial knowledge of these perspectives is supposed to be acquired through wall-following strategies by visually impaired people (W. H. Jacobson, 1993). As reviewed by Lahav & Mioduser (2008) and reported by Sjöström et al. (2003), support for non-visual acquisition of spatial knowledge can be effectively addressed by the strength of virtual haptic-audio interfaces. In order to evaluate the usability of haptic-audio interfaces that support non-visual way-finding functionalities of novel indoor environments, an empirical study was conducted. The experimental stimuli were constrained to palm-structured floor plans with three independent functional rooms, individually labeled as bathroom, kitchen, and sleeping-room. The rooms were all directly, and only connected, to the hallway by one door (J. Yu & Habel, 2012).

For both sighted (Blades, 1990; Billinghurst & Weghorst, 1995) and visually impaired people (Kennedy, 2003; Kennedy & Juricevic, 2006), sketches are a reliable source of spatial mental models so that the spatial knowledge of the represented indoor environment is examined by means of a sketching task. The evaluation of sketched floor plans was done by two independent reviewers complying with the proposed guidelines. A detailed discussion about the evaluation guidelines is available in Appendix A.

1.3.2 Layer II: Linear overlapping in representations of functional facilities

In spite of the fact that modern artificial lighting and ventilation facilities are highly ubiquitous, it is still hard to find a building without windows. Windows also provide people inside buildings with a source of first-hand information about the real-time weather, traffic, and so on. Natural ventilation is equally important for both sighted and visually impaired people. Besides, visually impaired people do not feel comfortable staying in totally closed spaces, as it can make them nervous and depressed. About 86%[4] of all visually impaired people still have remaining eyesight. More generally, visually impaired people perceive and benefit from windows in a multi-modality manner. As long as there are windows in the room, even when the windows are closed, people inside buildings can still hear sounds and noises from the outside. If it is necessary to know about the temperature or whether it is raining, opening a window and reaching out is the most efficient and reliable method. Concerning orientation and mobility of visually impaired people, windows, similar to doors, are usually the perfect spatial reference in indoor environments. Thus, rooms with or without windows make a practical difference for visually impaired people (see detailed discussion in Section 4.2.3). In terms of non-visual human-environment interactions, visually impaired people can keep track of the position of windows according to the light or sound emitted from the windows beyond their

[4] The latest data was published by World Health Organization in 2012. Retrieved from: http://www.who.int/features/factfiles/blindness/en/index.html

limited reach of limbs. Therefore, it makes sense to make spatial information of windows in indoor environments available to visually impaired people in a non-visual way.

In addition to windows, radiators are the second most common facilities in indoor environments. Similar to windows, radiators are considered as integral elements of internal surface of walls, since the majority of radiators are placed at a vertical height below the position of window, in vertical dimensions. These spatial relations can be described in a similar way to the temporal intervals proposed by Allen (1983). For instance, a radiator and a window can be located on a completely separate vertical wall section: If the radiator is partially below the window, they form a spatial overlapping relation in vertical dimension; or if the radiator and the window have the same width and the radiator is placed exactly below the window, then they occupy the same wall section in the vertical perspective. The position and spatial relations of windows and radiators define practical constraints to configure furniture pieces. A big wardrobe should not block the area of a window or a radiator, whereas a desk can be located directly at the wall section with a window, provided that there are no radiators directly below it.

Furthermore, power-outlets are also facilities that cannot be ignored. Particularly for visually impaired people, spatial knowledge of power-outlets need extra efforts to acquire, since searching for power-outlets can be a challenging and dangerous task. It is not sensible for visually impaired people to search for them with bare hands. And the closer power-outlets are approached, the more likely it is for visually impaired people to be trapped by other electric appliances or power cables. Therefore, spatial knowledge of power-outlets is covered in this representation layer. In realistic indoor environment scenarios, power-outlets are free from spatial overlapping relations between windows and radiators in vertical dimension. Consequently, two properties of the power-outlets on virtual floor plans are focussed: 1) the feasibility of distinguishing them from windows and radiators and 2) the position of power-outlets on the walls.

With regard to 2.5-D virtualization, it is worth noting that all the spatial knowledge representing the physical 3-D environment is projected to the bottom plane, which is the only plane explored by users. This fact explains how overlapping between spatial knowledge representations is caused in 2.5-D virtualization. For realistic indoor environments, functional facilities, such as windows, radiators, and power-outlets and their locations play an important role in determination of the actual function of rooms, as well as in mobility and orientation planning. Since all these functional facilities are always located on the vertical surfaces of walls, in 2.5-D virtualization must develop spatial constellations with linear overlapping involving walls and other entities of functional facilities.

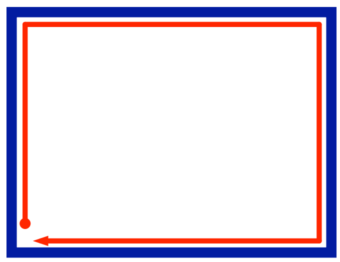
Furthermore, it is the analog spatial properties of these functional facilities that are of most practical concern to visually impaired people, such as their size and position. And as summarized by Picinali et al. (2014), both sighted people and visually impaired people are able to preserve metric properties in spatial mental models.

Therefore the challenge that has to be tackled in representation Layer II is to find an approach to represent spatial knowledge with linear overlapping for visually impaired users in an analog manner (see detailed discussion in Chapter 3).

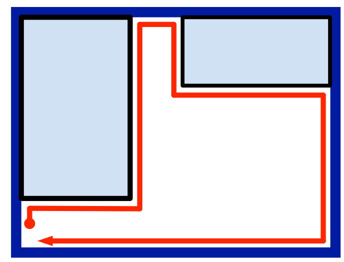
1.3.3 Layer III: 2-D overlapping between objects and regions

In addition to linear overlapping, 2-D overlapping also exists in haptic virtualization of indoor environments. The slight difference between 3-D and 2.5-D virtualization strategies is that 2-D overlaps can never be avoided. Dealing with finely-grained mobility and orientation tasks in novel indoor environments independently is a challenge visually impaired people have to face. When visually impaired people are required to stay longer than a temporary visit or work extensively in a new place, they need to acquire spatial knowledge. An example: When a visually impaired person would like to select an appropriate hotel room, a holiday apartment, or a new office, more intensive mobility and orientation is involved and explicit spatial knowledge of all the furniture pieces and objects is required. So in addition to the mental spatial model acquired from representation Layer I and II, acquisition of spatial knowledge about pieces of furniture and objects should be further supported. In this representation layer, two major issues are addressed.

First, moving and exploring in the different rooms and areas of a represented indoor environment should not be negotiable. Although employing non-visual representations of furniture is supposed to increase the complexity of virtual haptic floor plans, spatial knowledge acquisition of shapes and areas, as well as facilities, should not be influenced in a negative manner. Nevertheless, with regard to realistic situations, furniture pieces are typically placed exactly along the walls, which may considerably distract users from perceiving and following of the walls (as illustrated in Figure 1.3). In order to solve this problem, the approach proposed in this dissertation is to divide non-visual spatial knowledge acquisition through furnished virtual floor plans into two phases. The first phase provides users with spatial information addressed by representation Layer I and II, with no access to furniture pieces. Then, as soon as in the second phase, spatial knowledge of furniture pieces is represented non-visually. This strategy affords the advantage that users are able to acquire fundamental spatial knowledge of the represented indoor environment without paying extra attention to pieces of furniture. When spatial knowledge of furniture is desired, it can be added on the established spatial mental model based on representation Layer I and Layer II.



(a) Exploration path in room without furniture pieces



(b) Exploration path in room with furniture pieces

Figure 1.3: Depictions of exploration paths in virtual haptic floor plans, with dark blue frames depicting the walls, light blue blocks depicting furniture pieces, and red lines depicting exploration path of users.

The second challenge is how to realize haptic-audio representations for pieces of furniture in virtual haptic floor plans. Apart from the propositional knowledge, such as name and function of a piece of furniture, spatial knowledge of furniture on floor plans has very rich analog properties, including position, size, shape, and orientation. To describe the properties of every single piece of furniture only with verbal assistance during non-visual exploration is not efficient. Although there are still possibilities remaining in representational multi-modalities of audio stimuli, increasing the complexity of knowledge representation inventory mapped to various sonification and multiplying training time and efforts for users. In comparison, haptic force feedback is supposed to support analog knowledge acquisition similar to perceiving and exploring rooms and areas in representation Layer I.

Therefore, virtualization of floor plans with pieces of furniture consists of two phases. The first phase addresses all the contents belonging to representations in Layer I and II. Spatial knowledge acquisition of furniture pieces is supported in the second phase, in which analog properties of furniture pieces are virtualized through virtual haptic force feedback and propositional information is uttered by verbal assistance.

1.4 Methodology and consideration

In order to establish a human-computer interface with novel interaction scenarios, haptic-audio virtualization is employed as a research platform. Propositional knowledge is uttered with verbal assistance. Virtual haptic force feedback is employed to support spatial knowledge acquisition of 2-D objects with analog properties. Sonification is employed to represent analog properties of linear facilities. A user-oriented research approach is followed.

In this dissertation, the needs, wants, and expectations of potential users, namely visually impaired people, are extensively attended. Small-scale studies are conducted during the prototyping and implementing phases of the interface. Debugging, adjustments, and upgrades are performed after feedbacks gained through questionnaires, interviews, and focus group studies. Within group repeated-measured design was employed to identify the influence brought by predictor variables quantitively. And between group design with both sighted and visually impaired participants can contribute to accumulate clues towards the classic open question: *Are sighted people and visually impaired people different?* Cognitive science, more specifically spatial cognition, is referred to during the evaluation procedures upon the spatial knowledge acquired via the haptic-audio interface.

Ethical concern for experiment participants were taken into consideration by following the guidelines published by the American Psychological Association (APA). All the participants were thoroughly informed about the background and purpose of the studies. The participants learned that the results do not refer to individual abilities in any perspective. All the personal information obtained during the studies, as well as all the data produced by participants, remains confidential. Before each session, a relaxing environment was created by friendly introduction conversation. Coffee breaks with beverages and snacks were scheduled.

According to the consultation from teaching experts at Shanghai School for the Blind[5], visually impaired people are sometimes slightly more introverted, and have a somewhat stronger sense of self-esteem. Therefore, every single procedure in the study was conducted pleasantly and slowly, with a lot of patience. If visually impaired participants were involved in the study, apart from the study conductor or moderator, at least one class teacher from the school was present to support orientation and mobility of visually impaired participants if support was required. Throughout the focus group study, each session consisted of six visually impaired

[5]Shanghai School for the Blind is a boarding school with a history of more than a century (founded in year 1912). The work of teachers at Shanghai School for the Blind may not be exactly the same as the work of other common teachers. To take care of the students's everyday concerns always has a higher priority than almost everything else at this school. Everyday, from getting up to going bed, students are accompanied by their teachers. While the campus was under construction from August to December 2012, the teachers visited the students at home to give classes. The relationships between students and teachers are more like between family members. When familiar teachers are present, the students are supposed to behave more naturally and feel less stressed and embarrassed.

participants and two teachers were invited to participate to make the environment more familiar to the students.

1.5 Outline of the chapters and studies

The target of this work was to enable visually impaired people to perceive and acquire spatial knowledge of furnished novel indoor environments in an analog manner. A further contribution of this dissertation is the solution for non-visual representation of spatial knowledge, involving both linear and 2-D overlapping. The final targets can be divided into the following several research questions:

1. How can empty indoor environments be represented to visually impaired people in an intuitive and efficient way? This topic may cover the following sub-questions:
   - How is boundary-following in exploring and familiarizing with novel environments supported through virtual haptic interface?
   - How is division and access of each area in indoor environments represented in an appropriate way? And how should transitional access functions (doors) be implemented?
2. How can users perceive and interpret overlapping constellations between walls and functional facilities in 2.5-D haptic-audio floor plans? The analog properties (sizes and positions) of the functional facilities should be taken into consideration.
3. Do users desire non-visual access to spatial knowledge of furniture pieces? And how is it realized?
4. How can the acquired spatial knowledge be tested and evaluated with visually impaired participants?

In Chapter 2, the first virtual haptic-audio floor plan was implemented. With support from both virtual haptic force-feedback and audio assistance, non-visual access to the layout of the represented apartment was provided. An ad-hoc of the virtual floor plan with windows embedded in walls was represented using sonification. Study I was conducted to validate the usability of layout representations of floor plans.

In Chapter 3, the usability of sonified windows in Study II is described. Results show that windows can be recognized correctly in a qualitative manner. However, the accuracy of size and position reproduction of windows is not as good as expected. Therefore, the question of usability regarding the accuracy of analog knowledge represented by haptic-audio interaction scenarios is raised from the results. In order to isolate this question from a cognitive context, Study III was conducted. In addition, the representational multi-modalities of audio stimuli for representing spatial knowledge of multiple overlapping linear objects (virtual haptic walls with sonified windows, radiators, and power-outlets) was tested empirically in Study IV.

Chapter 4 covers the final empirical study (Study V) that tests the usability of a haptic-audio interface that representing a hotel room to users. On the hotel room plan, all the fixed facilities like windows, radiators, and power-outlets were represented through sonification, and pieces of furniture were also non-visually accessible. Study V was first conducted with sighted participants and then with visually impaired participants. Furthermore, the agenda of this study also enabled comparisons between sighted and visually impaired participants.

I summarize my work in Chapter 5. Open issues, as well as suggestions and outlooks for future research, are discussed.

Chapter 2

Regions and shapes of indoor environment

2.1 Elementary entities of virtual floor plans

Non-visual acquisition of knowledge with respect to shapes and areas can be efficiently and intuitively supported by haptic exploration of the boundaries in external representations. In the scenario of an indoor environment, it is the virtual haptic force feedback rendered during exploration of adjacent wall sections that affords the required functionality for knowledge acquisition. Doors in virtual floor plans are integral parts of walls and, at the same time, they provide the functionality of boundary exploration for shapes and areas. However, doors also connect areas and make them accessible. This fact defines the second functionality of doors in virtual floor plans, which is to enable the transitional manipulation of users during haptic exploration of virtual floor plans. This means that doors afford two concurrent knowledge representation functionalities in virtual haptic environments. Therefore, the major challenge to represent shapes and areas of indoor environments is to make sure that satisfying usability of the required functionalities is achieved by appropriate haptic virtualization, which is also elaborated on by J. Yu & Habel (2012).

2.2 Haptic-audio virtualization of elementary entities

As mentioned above, walls are one of the most elementary components of indoor environments. They define the boundaries of the environment from outdoors, as well as further divide the entire indoor environment into more specific regions or areas. Therefore, two types of walls are defined, namely external walls which define the global exterior boundary of the indoor environment represented, and internal walls which separate the spaces of the entire indoor environment into smaller areas.

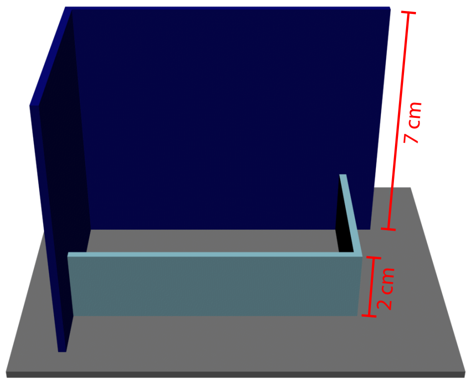


Figure 2.1: Depiction of a fragment of virtual haptic stimuli employed as walls for virtual floor plans, in which the grey plate represents the ground of the indoor environment; the dark blues blocks (with a height of 7 cm) represent external walls; and the light blue blocks (with a height of 2 cm) represent internal walls.

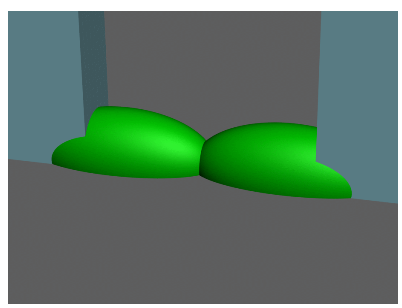


Figure 2.2: Depiction of stimuli employed as doors in virtual floor plans. The virtualization of a door consists of two slim ellipsoids. Their curves are haptically perceivable during wall-following exploration of users. Additionally, users can travel through the door in between the two ellipsoids.

The door is a further type of elementary component in indoor environments. It is a part of the wall and, at the same time, it also affords the access functionality between two different areas on both sides of the door. Therefore, in the first place, doors should not destroy the continuity of wall-following in virtual haptic floor plans. Second, doors have to be qualitatively perceivable. The first employed virtualization for doors in virtual haptic floor plans is illustrated by Figure

2.2. Detailed report and discussion about haptic-audio virtualization for doors is documented in Appendix B.

In order to evaluate the usability of the haptic virtualization for walls and doors in virtual haptic floor plans, a usability study was conducted.

2.3 Knowledge acquisition of regions and shapes (Study I)

2.3.1 Introduction

This section reports on the first empirical study with haptic-audio floor plans that could be used by visually impaired people (see Fig. 2.3). The goal of the study is to observe users' behavior while operating the haptic-audio interface and to evaluate the usability of these multimodal interface for spatial knowledge acquisition in the regions and areas of indoor environments. It is particularly interesting to investigate the level of preciseness with which the analog properties of haptic-audio floor plans could be interpreted and reproduced and whether its users desire more explicit analog knowledge. And if so, how to further represent analog knowledge in a non-visual manner. In addition, the study reported here contributes to develop, refine and evaluate the haptic-audio floor-plan exploration before testing the system with visually impaired people.

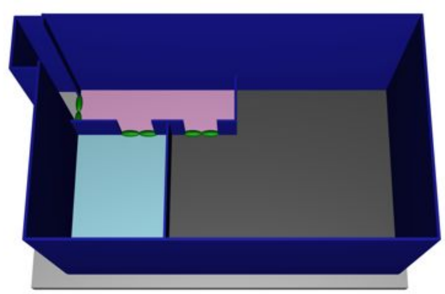


Figure 2.3: Example of virtual haptic models employed in a haptic-audio floor plan.

2.3.2 Method and stimuli

A repeated-measures study with 20 sighted participants (11 female, 9 male, mean age: 23.8 years, SD: 2.28 years) was conducted. They were all university students that had little or no experience with haptic force feedback devices. Each participant took part in all four sections of the experiment, namely, the introduction section, the training section, the experiment section, and, finally, the interview section.

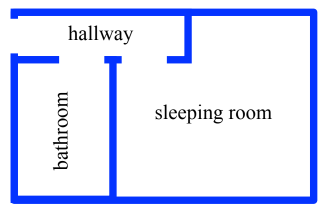


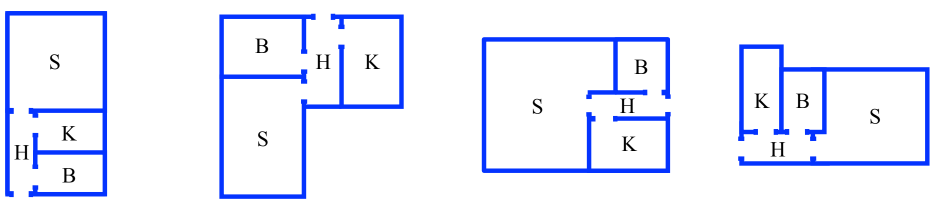
Figure 2.4: Haptic-audio floor plan employed in the training section of Study I.

In the introduction section, participants received all the necessary information and instructions for the whole study. In the training section, participants had the chance to accumulate first-hand experience exploring a haptic-audio floor plan. The training floor plan was a floor plan with one hallway, one bathroom and one sleeping room. The represented apartment was globally rectangular, but bared local L-shape for the sleeping room (see Figure 2.4). When participants touched the virtual haptic model of the floor plan with the stylus, virtual force feedback was rendered. When participants entered a specific room, the categorical knowledge of the room type was uttered through TTS audio. During the exploration of the haptic-audio room plan, sighted participants were asked to wear blindfolds, and they were encouraged to ask questions and report anything they considered uncomfortable. There were no time limits for the exploration of the floor plan. After the participants had finished the exploration, they were to resolve three tasks. Participants were first asked to reproduce a sketch of the floor plan on a 12 cm by 12 cm sized box printed on the answer sheet. The study conductor collected the sketch immediately after it was done. Their next task was a size-ordering task, which involved formulating a chain of inequations to present the relative size of all the four different rooms in the apartment. For example:

$$sleeping\ room > kitchen > bathroom = hallway \tag{2.1}$$

Means: The sleeping room was the largest room; the kitchen was the second largest; the bathroom and the hallway were the smallest and they had the same size. The third task was to report the shape of each room and area, as well as the global shape of the whole floor plan. Participants were asked to report in any case, whether it was rectangular, L-shaped, horizontally or vertically elongated. The answers of the shape confirmation task were taken as reference during the evaluation of the sketches. There was no time limit for exploring the floor plan, nor for either of the testing tasks. When the training section was finished, participants were allowed a break of 10 to 15 minutes.

In the experiment, since variations on floor plan features have different influence on human recognition (Ishikawa et al., 2011), we composed four different floor plans based on realistic apartments. The floor plans always had a hallway and three other rooms: one bathroom, one kitchen, one sleeping room, and one hallway. All the three rooms had, and only had one door connoting to the hallway. The entrance doors of all four apartments were placed on four different sides of the apartment, so that the direction of entering the virtual floor plan was balanced. Floor plan No. 1 was rectangular both globally and locally. Floor plan No. 2 was globally L-shaped and locally rectangular. Floor plan No. 3 was globally rectangular and locally L-shaped. And Floor plan No. 4 was L-shaped both globally and locally shapes (see Figure 2.5). In order to discard the order effect of the experimental conditions (four different virtual floor plans), the Latin Square Design was used (Bradley, 1958) (see Table 2.1). Same as in the training section, participants were asked to do the sketching task, the size ordering task, and the shape confirmation task after each exploration.



(a) Floor plan No. 1 (b) Floor plan No. 2 (c) Floor plan No. 3 (d) Floor plan No. 4

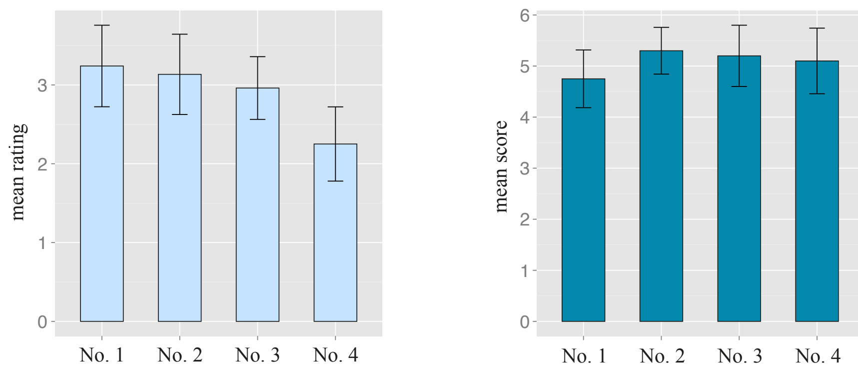
Figure 2.5: Depictions of floor plan stimuli employed in the experiment section of Study I, where the letter B stands for bathroom, H for hallway, K for kitchen, and S for sleeping room.

In the interview section, participants filled in a usability questionnaire. They were encouraged to share their comments and remarks upon the haptic-audio interface, as well as the experience of participating the study. As wording influence was taken into consideration, reverse-phrases were used for composing statements and questions from the questionnaires throughout this dissertation (Payne, 1951; Gaskell et al., 1993). Besides, in order to eliminate possible bias aroused by the order of questions in questionnaires, each participant received randomly arranged questions and statements (Schriesheim & Hill, 1981). At the end of the interview section, emerging topics were also discussed.

Table 2.1: Experimental condition assignment of Study I.

Participant ID	Concequence of the floor plans explored			
VP 1	No. 1	No. 4	No. 2	No. 3
VP 2	No. 2	No. 1	No. 3	No. 4
VP 3	No. 3	No. 2	No. 4	No. 1
VP 4	No. 4	No. 3	No. 1	No. 2

2.3.3 Results



(a) Evaluation of the sketching task (b) Evaluation of the size-ordering task

Figure 2.6: Evaluation results of four different floor plans employed in study I. As illustrated in Figure (a), the sketching task displays decreasing ratings from floor plan No. 1 to No.4. A statistically significant difference was only discovered between the mean value of floor plan No. 1 and No. 4 ($p < .05$). Figure (b) shows that participants achieved good rating in the size ordering task was achieved by participants ($F(3.76) = 1.51$, $p > .05$).

The scores of the sketched floor plans were determined by two independent reviewers under the supervision of the rating criteria established and validated in Appendix A. The ANOVA test showed that the scores of the sketches were significantly affected by the specific floor plan explored ($F(3,76) = 5.57$, $p < .05$, see Figure 2.6(a)), as the sketches of floor plan No. 1 typically had higher rates than the other floor plans. The Bonferroni post hoc test revealed that the performance of floor plan No. 1 was significantly better than that of No. 4, ($p < .05$). This implies that the L-shape had influence on producing sketches after the exploration

(a) Example sketch of floor plan Nr. 3 (b) Example sketch of floor plan Nr. 4

Figure 2.7: Examples of sketches produced by participants.

of the virtual floor plan. The weakness revealed in the sketches of No. 3 and No. 4 was mainly from failing to reproduce global and local L-shapes.

To analyze the results of the size-ordering task, the chain of inequations representing the size order of the four rooms was first decomposed into six binary inequations. The derived six binary inequations corresponding to inequation-chain 2.1 would be:

1. sleeping room > kitchen
2. sleeping room > bathroom
3. sleeping room > hallway
4. kitchen > bathroom
5. kitchen > hallway
6. bathroom = hallway

Each correct answer scored one point. So the total score of this task ranged from 0 to 6. The performance was fairly good and did not significantly change over the four different virtual floor plans ($F(3.76) = 1.51$, $p > .05$, see Figure 2.6(b)). The most common mistake with respect to floor plan No. 1 was to think the kitchen was larger than the bathroom. Since in most residences, kitchens are larger area than bathrooms, life experience of participants was assumed to have influence on the size-ordering task. The lower mean scored by floor plan No. 1 was explored could result from the fact that the kitchen, the bathroom and the hallway had very similar size. Further more, the bathroom and the kitchen were equally sized, which lead to a comparably larger number of errors in the inequation-chain.

Results of the questionnaire are summarized in Table 2.2. The participants used the 5-point *Likert scale* for their answers: 1 meant *totally agree* and 5 meant *totally disagree*. The conclusion was largely in line with our hypothesis that participants are able to perceive the walls and doors of virtual haptic floor plans. Verbal assistance was also considered as helpful for getting familiar with the apartment represented. And participants did not think it very challenging to figure out global

Table 2.2: Summary of answers to the questionnaire in Study I (1 meant *totally agree*, 5 meant *totally disagree*).

Nr.	Question / Statement	Mean	SD
1.	It was challenging for you to understand the interaction pattern of the virtual haptic device.	3.75	0.79
2.	The verbal assistance telling the names of rooms was not helpful for getting familiar with the apartments.	4.20	0.70
3.	It was easy to perceive the walls of the represented apartment.	1.55	0.75
4.	It was easy to figure out different accesses to all invidual rooms.	2.90	0.55
5.	It was easy to tell internal walls and external walls from one another.	2.60	1.10
6.	It was challenging to estimate the length of the walls.	3.80	0.77
7.	It was easy to figure out the global layout of the apartments.	1.60	0.94
8.	It was challenging to figure out the shape of the rooms.	2.25	0.91
9.	It was easy to figure out the size of the rooms.	1.90	1.25
10.	The experience of using this interface was pleasant.	2.25	0.79
11.	You would recommend this interface to someone else who is blind or visually impaired.	1.80	0.70

layout of the apartment, as well as shape and size of individual rooms. However, it was challenging for them to estimate the length of the walls. In general, participants thought the virtual haptic floor plan interface was easy to adapt to, and using this kind of interface was a pleasant experience for them. If they had friends or acquaintances who were visually impaired, they would be very likely to recommend our interface.

2.3.4 Discussion

With this study, we have proven that it is feasible to get familiar with the interface and the mapping between the stimuli and the corresponding spatial knowledge represented in a reasonably a short period of time. Furthermore, when the wall-following strategy was supported by virtual haptic force feedback and the doors were also haptically perceivable, it was plausible to acquire spatial knowledge of small-scaled apartments. Participants were able to acquire specific knowledge of including the number of the rooms, the access to the rooms, the geometrical features of the rooms, and the entire apartment. In addition, to have verbally assisted room names during virtual haptic exploration was helpful to users for identifying specific rooms and areas on floor plans.

However, the analog properties of floor plans were not always accurately reproduced in the sketching task. For example, the local L-shape on floor plan No. 3 and 4 was not always reproduced. The proportion of the two edges of the concave corners and the size of negative space seemed to be predictor variables affecting participants perception and cognition of participants (see Figure 2.8(a)). Based on this hypothesis, further exploratory study was addressed by a bachelor thesis in association to the CINACS research training group (Schlesinger, 2013). According to the results of empirical study, it has been proven that there was an interaction influence due to the position of the door and the concave-edge-proportion (CEP) ratio of a specific room. When the door was located next to the shorter concave edge of the inside corner, and one concave-edge is longer than the other by at least 3.25 times, the discontinuity in haptic exploration, due to the concave-corner could have been confused with the feedback aroused by the doors. As a result, the concave-corners were very likely to be ignored by users.

(a) Concave-corner-edges of L-shaped rooms (b) Negative space of L-shaped rooms

Figure 2.8: Illustration of property variables of L-shaped rooms.

Another relevant factor affecting local L-shape recognition seemed to be the proportions between the negative area and the L-shaped area itself, which is the ratio of a shadowed area over a non-shadowed area, as in Figure 2.8(b). The smaller ratio value is, the less likely for the L-shape to be reproduced.

On the other hand, even in the case of non-salient L-shaped rooms, and although the shorter angle would not be likely to afford a substantial function from a practical and cognitive perspective, still there were still participants that did reproduce the L-shaped rooms correctly. It implies that it is actually possible for users to find the more finely-grained, analog properties of the rooms. And in the interview section, rather than to ask for more explicit information upon the analog properties of the floor plans, users granted positive comments on the employed interaction algorithm for its easy-to-use feature and claimed that they were satisfied with the level of accuracy of the knowledge they were able to achieve from the floor plans.

2.4 Summary

In this chapter we proposed to utilize current virtual haptics technologies to realize an appropriate, non-visual substitution for traditional visual floor plans that can be used by visually impaired people. The first haptic-audio floor plan was implemented to make the most elementary components of floor plans non-visually accessible, namely walls and doors.

Usability study of this prototype was conducted with blindfolded sighted participates. The spatial knowledge acquired by the participants was evaluated based on a sketching task, a size-ordering task, and a room shape confirmation task. For the purpose of evaluating the sketched floor plans in a relatively subjective manner, rating criteria was established and validated in advance.

In the virtual models employed in this prototype, walls were represented as ridges with different heights. These ridges were 7 cm tall and represented external walls, while those 2 cm tall ridges represented internal walls that define the rooms inside an apartment. Depending on the virtual haptic force feedback users could explore the floor plan by utilizing the boundary-following strategy. All participants used wall-following strategies spontaneously, proving that the *perimeter room-familiarization procedure* (W. H. Jacobson, 1993) is also a reliable and efficient strategy in virtual environment. The capability of participants to distinguish doors from walls during wall-following movements proves the usability of representational multi-modality of haptic channels in virtual environments (Grünwald, 2008).

All the participants succeeded in figuring out the correct topology of all the four different floor plans. Neither was it a challenge to acquire analog properties, such as size, shape, and perspective ratio of individual rooms and entire floor plans. The names of the rooms were uttered by TTS verbal assistance when a haptic interaction point entered the corresponding rooms.

Participants were able to tell the relative size of the rooms very well. And it was not challenging to figure out the perspective ratio of individual areas, depending on the virtual force feedback received during haptic exploration, which supports our hypothesis. Furthermore, participants were also able to figure out the global shape of the apartment represented, although it was not explicitly represented on the floor plan. This result confirms the the argument by Tversky (1993) that people do have inference abilities based on the spatial information they comprehended.

Although the reproduction of non-salient L-shaped spaces was not as good as in the rectangular spaces, the participants did not desire more explicit assistant information. In real life, a non-salient L-shaped room is not considered as significantly different from a rectangular room out of practical concern, since the shorter angle of an L-shaped room is not supposed to afford practical functionality.

With this haptic-audio interface at hand, we are on the safe ground of elementary infrastructure of non-visual floor plans. As a matter of fact, usually there are many more entities that can be represented in a traditional visual floor plan, such as windows. Similar to sighted people, visually impaired people also regard windows as important functional facilities of indoor environments. In the following sections, further research on how to represent windows and other functional facilities in 2.5-D haptic-audio floor plans are reported.

Chapter 3

Linear overlapping in representations of functional facilities

3.1 User expectations on spatial knowledge of functional facilities

Throughout this dissertation project, user-centered principles are highly respected. Parallel to the virtualization and usability testing work, direct contact with real potential users, namely visually impaired people, was established. As a result, it has been possible to learn about user expectations and to collect feedback at early stages, as well as to adjust and to further implement haptic-audio interfaces in favor of real potential users.

Through a focus group study, plenty of valuable information was collected. One of the major conclusions was that spatial knowledge of functional facilities, such as windows, radiators, and power-outlets, achieved from virtual haptci-audio floor plans was mostly desired by visually impaired people (a detailed report and discussion about the focus group study with visually impaired people is documented in Appendix C).

Windows are openings in walls, which leads to the conclusion that in a bird-eye perspective representation of indoor environments, windows (partially) occupy the same space as the walls they are embedded in. These constellations are referred to as *spatial overlaps* through out this dissertation.

In traditional visual 2-D floor plans, spatial overlaps between walls and windows are usually represented by symbolic depiction or color coding (see Figure

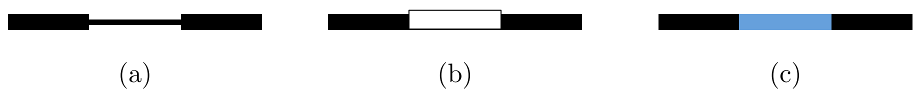


Figure 3.1: Various depictions of window in traditional visual floor plans.

3.1) represent analog properties [1] of windows (such as width and position) in an intuitive manner. In 2.5-D virtual haptic floor plans, window-following is naturally included in wall-following. Therefore, non-visual representation for such spatial overlap relations during haptic exploration of wall-following should be implemented. Theoretically, knowledge of windows could be represented either haptically or acoustically. However, unlike doors, windows occupy larger portion of the walls. Therefore, when the width of a windows is represented by featured haptic stimuli, this feature must cover the entire wall section occupied by the windows. If this is the case, it is worth noticing that modified haptic features, such as friction, may affect exploration velocity during wall-following. If the length of a wall section with modified haptic stimuli is not negligible, it can easily introduce artifacts to the estimation of sizes and shapes of virtual haptic objects. So, to represent analog properties of windows using virtual haptic features is not considered as optimal approach.

On the other hand, provided that the analog properties of windows were represented using verbal assistance, digits for the width and descriptions for the position should be applied. In order to listen to verbal assistance and make sense of its contents, users have to stop or suspend the ongoing haptic exploration, which will disturb its continuity. Fortunately, there is sonification (non-verbal sound) that provides a promising solution for the current information overload situation (Brewster, 1997). In comparison to verbal assistance, sonification is not capable of communicating large amounts of sophisticated contents, but it is powerful in representing a specific message in a given context (Nees & Walker, 2009).

A proposal for the non-visual representation of overlap spatial relations between walls and windows is to map sound and silence of a certain type of sonification to the occurrence and absence of a window during wall-following. The hypothesis is that the position of windows can be interpreted by integrating a hand position during wall-following and by playing a corresponding sonification. Users are able to interpret the width of windows by integration their exploration velocity during wall-following together with the time duration of sonification.

[1] Here, the definition proposed by Palmer (1978) is again employed. Since representations of windows in either visual and haptic floor plans preserve the size and position properties of windows according to the windows represented in physical world.

3.2 Virtualization of functional facilities

3.2.1 Virtualization of windows and radiators

Based on the same floor plans employed in Study I, the virtual floor plans in this section were augmented by sonified windows. The window area was implemented to be slims stripes, seamlessly adhered to walls. The width of the window strips in predefined areas in the ground was always 5 mm, and the relative length was defined according to the window-wall length ratio in the stimuli (see Figure 3.2). When there was only one window in a room, the beep was pitched at 261.63 Hz in frequency (musical note C4). In case that there were two windows in the same room, the frequency of one window would stay at 261.63 Hz, while the other one would have 1046.50 Hz (musical note C6). These strips were not haptically perceivable, but the sonification would fire out when users touched these areas with the haptic interaction point. The sonification used was implemented to be continuous harmonic beeps, which fire out when the window areas were touched by the haptic interaction point. The volume of sonification with different frequencies was adjusted to the same level by referring to equal-loudness contours (Bauer & Torick, 1966) and pilot trials. So in the first place, the participants are supposed to be aware of the existence of the window(s) even during haptic exploration at very high speed (ca. 15 cm/s). Provided that users are interested in the length of windows, they may integrate the speed of the their haptic exploration with the time duration of the sonification into an estimation of the length in proportion to the wall.

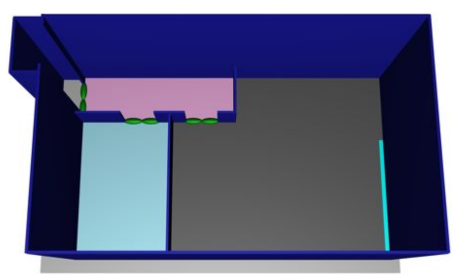


Figure 3.2: Depiction of a floor plan used in the training section of Study II.

Similar to the virtualization of windows, haptically unperceivable areas for sonification were defined. These areas were also placed exactly along the walls with a width of 5 mm. In order to easily to distinguish two sonification stimuli, a distance of half a musical note in frequency was employed. A harmonic tone of 277.18 Hz (musical note C# 4) was used for radiators. Additonally, salient rhythm was implemented. However, synthesizing audio stimuli is not addressed in this dissertation.

3.2.2 Virtualization of power-outlets

Different to doors, power-outlets occur more frequently in rooms. So, if power-outlets were represented by novel feature of virtual force feedback, continuity of wall-following would be influenced more severely. On the other hand, there is still enough space in representational multi-modality of audio stimuli to make use of. Therefore, it would be better to represent power-outlets as haptically unperceivable, which is similar to the design of windows and radiators in Study III (see Section 3.4.2 for detailed discussion). But, differing from windows and radiators, power-outlets do not cover a significant section of walls. Instead, they only occupy socket space on walls. So I propose that all the designated areas for power-outlets would have uniform sizes, only as large as necessary to represent their positions.

Based on the feedback gained from a couple of corridor testing trials, we assigned the designated areas of power-outlets as $5 \times 5 \times 5$ mm cubic space, and the sonification employed was a harmonic sound at 1046.5 Hz (musical note C6). In order to prevent participants from being exposed to inconsistent volume, again equal-loudness contours were consulted for setting the volume of all acoustic stimuli (Bauer & Torick, 1966).

For the next step, empirical studies were conducted so as to investigate the usability of our haptic-audio interface when three different types of sonification were employed.

3.3 Knowledge acquisition of sonified windows (Study II)

3.3.1 Introduction

To investigate the usability of sonification employed to representing spatial overlap relations in virtual floor plans and analog knowledge of windows, a usability study was conducted. Based on the same virtual floor plan stimuli employed in Study I, windows were represented by sonification.

The sonification stimuli employed in this study is implemented through harmonic sine waves, so as to make this exploratory study easy to implement and manipulate. Within designing, implementing, and testing procedures of haptic-audio floor plans, we focus on the plausibility and usability of sonification, disregarding aesthetics perspective that lies beyond usability concerns and the scope of this dissertation. Besides, the influence brought on floor plan layout recognition and reproduction by integration with sonificaiton is also an important research point.

3.3.2 Method

A total of 16 participants contributed to this study (eight female, eight male, mean age 24.19 years, SD: 3.12 years). Sighted university students with little or no experience with haptic force feedback devices were recruited. More importantly, they did not participate in Study I. The same as Study I, there were four sections in the study: the introduction section, the training section, the experiment section, and the interview section.

For the four original floor plans, two different window configurations were implemented, individually named as *a* and *b*. There were two or three windows in each apartment, usually with two windows in one room. The value of *window-wall ratio* varied varied between 0.25 and 1.

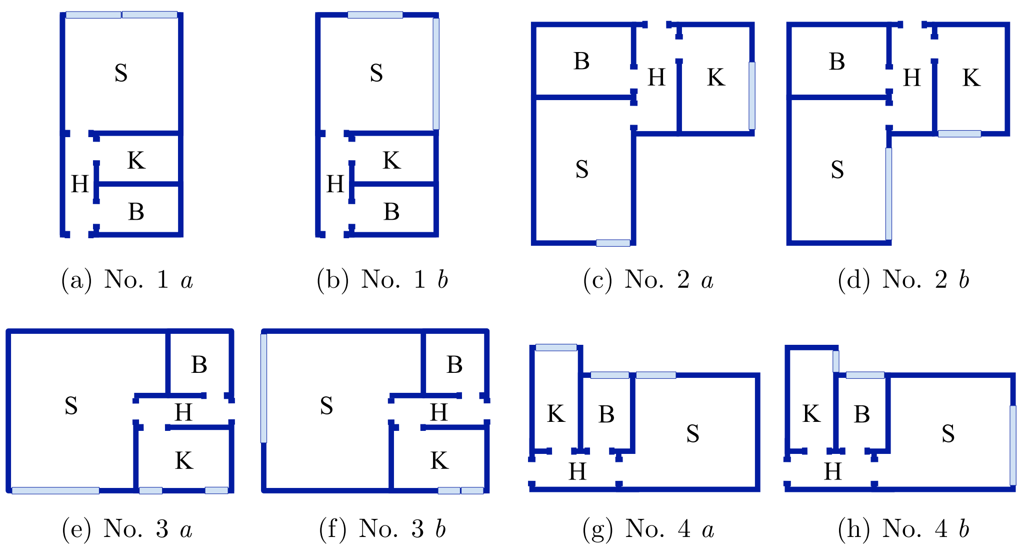


Figure 3.3: Depictions of floor plan stimuli *Set a* and *Set b* employed in the experiment section of Study II; the letter B stands for bathroom, H for hallway, K for kitchen, and S for sleeping room.

All of the stimuli employed in the experiment section are illustrated in Figure 3.3. For stimuli of both sets, the sonified windows were always embedded in the external walls of the apartment. They were placed either in the middle of walls, or at either end of the walls. In Set *a*, windows on floor plan 1, 3, and 4 were located on the rather same side of the apartment. In Set *b*, windows were located on adjacent wall of the apartment and all the walls with concave-edges in the entire apartment were modified with windows. The rooms that have windows remain the same between the two sets.

Exemplified in Table 3.1, as experimental conditions, the virtual floor plans were assigned to participants according to a specific Latin Square. Each participant explored four floor plans that either all belonging to variation Set *a* or variation Set *b*. The total number of virtual floor plans for each window configuration was counterbalanced. After each exploration, participants went through the same tasks as in Study I. In the interview section, they gave their opinion on their experience with the haptic-audio interface for non-visual floor plans.

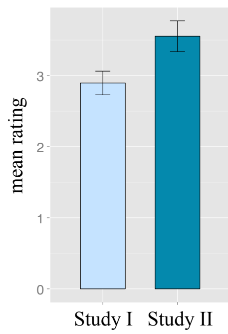
Table 3.1: Experiment condition assignment for participants of Study II.

Participant	**Concequence of floor plan explored**				**Participant**	**Concequence of floor plan explored**			
VP 1	No. 1 (a)	No. 4 (a)	No. 2 (a)	No. 3 (a)	VP 9	No. 1 (a)	No. 4 (a)	No. 2 (a)	No. 3 (a)
VP 2	No. 2 (a)	No. 1 (a)	No. 3 (a)	No. 4 (a)	VP 10	No. 2 (a)	No. 1 (a)	No. 3 (a)	No. 4 (a)
VP 3	No. 3 (a)	No. 2 (a)	No. 4 (a)	No. 1 (a)	VP 11	No. 3 (a)	No. 2 (a)	No. 4 (a)	No. 1 (a)
VP 4	No. 4 (a)	No. 3 (a)	No. 1 (a)	No. 2 (a)	VP 12	No. 4 (a)	No. 3 (a)	No. 1 (a)	No. 2 (a)
VP 5	No. 1 (b)	No. 4 (b)	No. 2 (b)	No. 3 (b)	VP 13	No. 1 (b)	No. 4 (b)	No. 2 (b)	No. 3 (b)
VP 6	No. 2 (b)	No. 1 (b)	No. 3 (b)	No. 4 (b)	VP 14	No. 2 (b)	No. 1 (b)	No. 3 (b)	No. 4 (b)
VP 7	No. 3 (b)	No. 2 (b)	No. 4 (b)	No. 1 (b)	VP 15	No. 3 (b)	No. 2 (b)	No. 4 (b)	No. 1 (b)
VP 8	No. 4 (b)	No. 3 (b)	No. 1 (b)	No. 2 (b)	VP 16	No. 4 (b)	No. 3 (b)	No. 1 (b)	No. 2 (b)

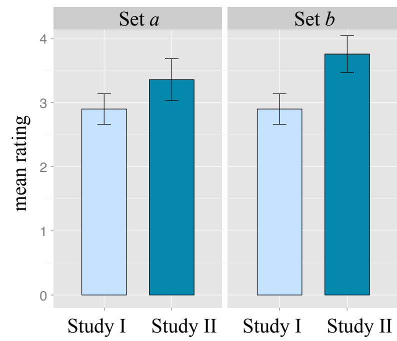
3.3.3 Results

The results of the sketching task show that, on average, the sketches produced by participants from Study II were rated higher than in Study I ($mean_I$=2.90, $mean_I I$=3.55, $p < .001$). And, individually, the participants of both Set *a* and Set *b* in Study II also showed significantly better quality than those in Study I ($mean_{IIa}$=3.36, $p_{IIa} < .05$, $mean_{IIb}$=3.75, $p_{IIb} < .001$, see Figure 3.4). In general, the performance of Set *a* and Set *b* did not significantly differ in statistics ($p >$ .05). This implies that the difference between two window configurations did not have a significant influence on the quality of sketches produced by the participants.

In the perspective of floor plans, except the performance of Set *a* in floor plan No. 1, sketches produced in Study II were rated as better than those in Study I, though statistic differences were only found between performance in floor plan No.



(a) Comparison of sketching task between Study I and Study II.



(b) Comparison of sketching task between Study I and two sets in Study II.

Figure 3.4: Summary of comparison in sketching task of Study I and Study II. Between Study I and Study II, the sketches produced in Study II were significantly better rated than those in Study I ($p < .001$). Significant difference was also discovered between the mean rating of Study I and two sets of Study II individually. Within Study II, the mean rating of sketches produced in Set *a* was not significantly different from that of Set *b*.

4 in both Set *a* and Set *b* ($mean_{I4}$=2.25, $mean_{IIa4}$=3.38, $mean_{IIb4}$=3.81, $p_{II4a} < .05$, $p_{II4b} < .001$, see Figure 3.5).

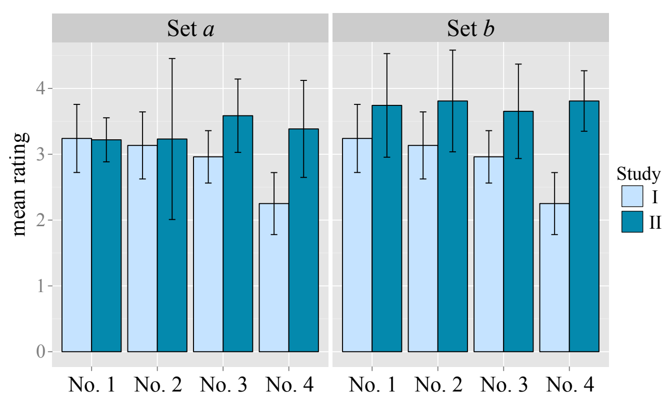
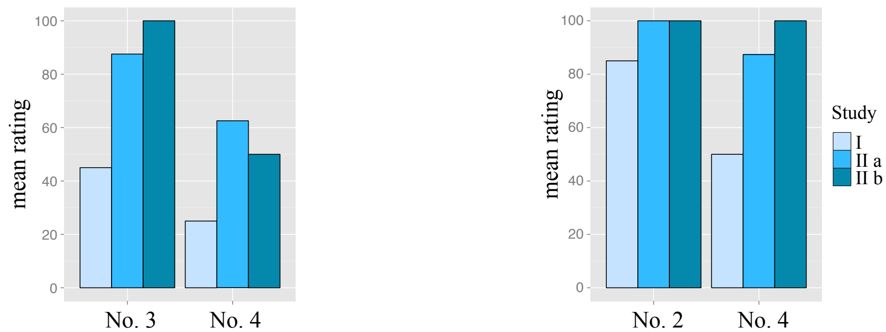


Figure 3.5: Comparison of sketching task between Study I and Set *a* and Set *b* of Study II in floor plan perspective. Although generally the mean ratings of sketches from Study I were were lower than those of both Set *a* and Set *b*, statistical significance was only discovered between mean ratings of floor plan No. 4.

The improved recognition of both local and global L-shapes in the stimuli resulted in a better quality of the sketches in Study II (see Figure 3.6). The



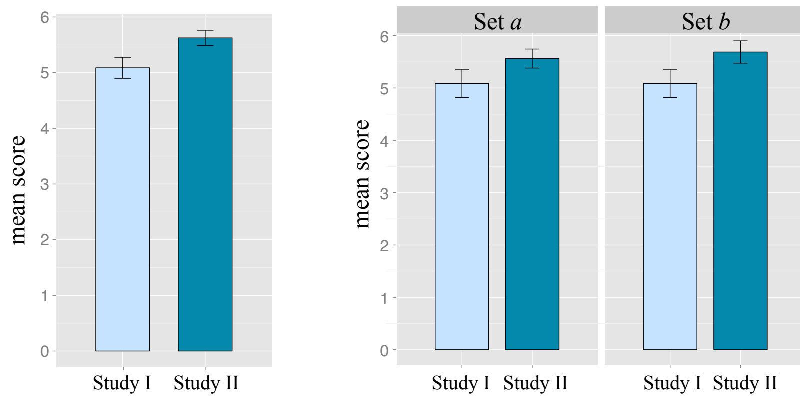
(a) Comparison of local L-shape reproduction between Study I and Study II.

(b) Comparison of global L-shape reproduction between Study I and Study II.

Figure 3.6: Comparison of L-shape reproduction between Study I and Study II. The availability of sonified windows on floor plans was significantly associated with the participants' ability to reproduce local L-shapes ($p < .01$) and global L-shapes correctly ($p < .05$).

availability of sonified windows on floor plans was significantly associated with the participants' ability to reproduce local L-shapes correctly ($\chi^2(1) = 7.4$, $p < .01$). In Study I, only 45% of the participants reproduced the locally L-shaped room on floor plan No. 3, while the participants achieved 100% and 87.5% in Set *a* and b respectively in Study II. For floor plan No. 4, the sleeping room was sketched as L-shaped by 25% of the participants in Study I, and by 62.5% in Set *a*, 50% by Set *b* in Study II (see Figure 3.6). Besides, the existence of sonified windows was also significantly associated with whether or not global L-shapes could be correctly reproduced ($\chi^2(1) = 5.9$, $p < .05$). The global L-shape of floor plan No. 2 was reproduced by 85% of the participants in Study I, and by 100% of the participants in Study II. Regarding the global shape of floor plan No. 4, 50% of the participants in Study I was able to reproduce the L-shape. In comparison, 87.5% and 100% of the participants in Set *a* and b were able to reproduced the global L-shape of floor plan No. 4.

In size ordering tasks, participants in Study II had higher scores than in Study I ($mean_I$=5.09, $mean_{II}$=5.63, $p < .001$). Although the differences in the amounts were small, they were statistically significant. This performance improvement size ordering tasks are limited to Study I and both Set *a* and *b* of Study II ($mean_{IIa}$=5.56, $p_{IIa} < .001$, $mean_{IIb}$=5.69, $p_{IIb} < .001$). However, the difference between Set *a* and Set *b* of Study II was not significant (see Figure 3.7). More specifically, the significance was mainly due to performance improvements of performance on floor plan No. 1($mean_{I1}$=4.75, $mean_{II1a}$=5.50, $p_{II1a} < .05$,



(a) Comparison of size ordering task between Study I and Study II.

(b) Comparison of size ordering task between Study I and two sets in Study II.

Figure 3.7: Comparison of size ordering task between Study I and Study II. Performance in Study II was significantly better than Study I ($p < .001$). The statistically significant differences were also discovered between the mean score of Study I and both Set a ($p < .001$) and b ($p < .001$).

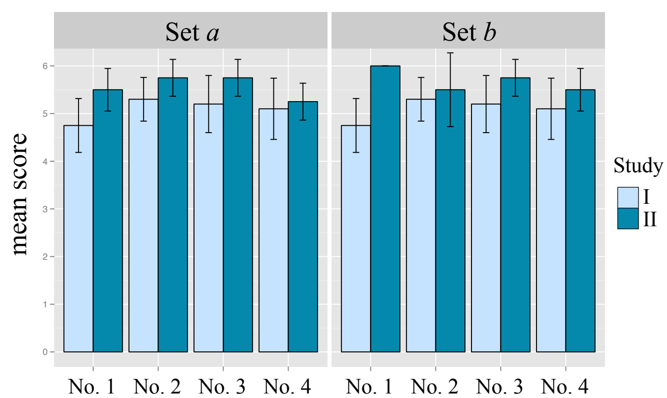


Figure 3.8: Comparison of size ordering tasks of Study I and Study II from a floor plan perspective. Although mean scores in Study I are lower than in Set a and Set b of Study II, statistical significance was only discovered between mean scores on floor plan No. 1 of Study I and Set a ($p < .01$) and Set b ($p < .001$) of Study II.

$mean_{II1b}$=6.00, $p_{IIb} < .001$). The differences between the performance of other floor plans were not statistically significant and the performance differences between Set *a* and *b* were never significant (see Figure 3.8).

All the participants were able to produce the sonified windows in the correct walls, which showed that using sonification in virtual haptic environment was a reliable approach to represent the occurrence of spatial constellation with linear overlap relations. Nevertheless, analog properties of windows, namely length and position, were not very precisely reproduced. Althrough the sketched window-wall ratio was significantly related to the ratio in the original models, $\tau = .40$, $p < .001$ (Kendall's tau). The amount of errors regarding window-to-wall proportions varied from 9% to 25% of the length of the wall, in which the windows were embedded (see Figure 3.9 for sketch and see Figure 3.3(h) for stimuli).

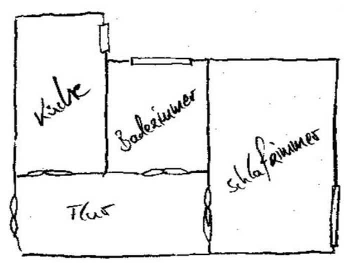


Figure 3.9: Example of sketches produced by participants in Study II, showing good quality in reproduction of layout of the apartment but low accuracy in window-to-wall proportion.

The answers given by the participants to the questionnaire are summarized in Table 3.2. Again, the participants used the 5-point *Likert scale* for their answers: 1 meant *strongly disagree* and 5 meant *strongly agree*. Similar to the results in Study I, participants thought that the interface was easy to get familiar with, the verbal assistance was helpful, using this kind of interface was a pleasant experience, and they would like to recommend this interface to visually impaired people (see Table 2.2). On average, participants who explored the sonified floor plans thought it was less challenging to figure out the size and shape of rooms than those who explored non-sonified floor plans in Study I. The difference between opinions on size estimation was statistically significant ($mean_I$ = 3.10, $mean_{II}$ = 3.88, $p < .05$). However, the difference between opinions on shape recognition was not statistically significant ($mean_I$ = 2.75, $mean_{II}$ = 2.31, $p > .05$).

Table 3.2: Summary of answers to the questionnaire in Study II.

Nr.	Question / Statement	Mean	SD
1.	It was challenging for you to understand the interaction pattern of the virtual haptic device.	1.31	0.79
2.	The verbal assistance telling the names of rooms was not helpful for getting familiar with the apartments.	1.81	0.75
3.	It was challenging to figure out the global layout of the apartments.	1.75	0.77
4.	It was easy to figure out the accesses to each invidual rooms.	2.81	0.54
5.	It was challenging to figure out the shape of the rooms.	2.31	0.95
6.	It was easy to figure out the size of the rooms.	3.88	0.81
7.	It was challenging to map the fire-out of sonification to existance of windows.	1.56	0.63
8.	The differently pitched sonification for windows was helpful for identifying different instances of windows.	2.63	0.96
9.	Having sonified windows is helpful for getting familiar with the apartments.	1.56	0.63
10.	It was easy to detect the windows.	3.69	0.79
11.	It was challenging to estimate the position of the windows in the walls.	3.31	1.08
12.	It was easy to estimate the length of the windows.	2.06	0.77
13.	It was important for you, to know about the information of the windows.	2.44	0.81
14.	The experience of using this interface was pleasant.	3.94	0.68
15.	You would recommend this interface to someone else who are blind or visually impaired.	4.56	0.51

3.3.4 Discussion

As implied by the results, participants could not only reproduce the correct number of sonified windows in the corresponding walls, but also produced better sketches after exploring the floor plans with sonification than those without. One of the direct causes was that participants were more likely to figure out the correct local and global shapes of the stimuli. On the other hand, estimating the sizes of different rooms on the floor plans also improved when the sonified floor plans were explored. It supports our hypothesis that using sonification in virtual haptic environments makes it possible to represent spatial knowledge with linear overlap relations, such as the window-wall constellation in the virtual haptic floor plan scenario, and that employing sonification does distract the exploring and recognizing the layout of floor plans. Besides, when the concave edges of the global L-shape are modified with sonified windows, the global L-shapes are more likely to be correctly reproduced by users. The reason could be that the participants spent more time in exploring the sonified wall sections.

On the other hand, there are also some usability flaws discovered in the course of this study. First of all, sonificaiton only resonates if the haptic interaction point keeps in contact with the predefined area on the ground, which is a plane 2D area. During a window-following movement, provided the users' hand is not free from shaking in the vertical dimension, the continuity of sonificaiton could be easily destroyed. This would aroused confusion, make exploration inefficiency and introduced an artifact, resulting in the poor estimation of window-wall proportions by the participants. So, a new design for area invoking sonification must be implemented. It should be able to tolerate noisy hand movement in vertical dimension so as to preserve the continuous sound of sonificaiton. Further, participants shared that they did not think it necessary and helpful to assign different frequencies to the sonification in order to highlight the number of the windows. Participants believed that it could rather slightly increase the users' mental efforts to map differently pitched sonificaiton to identity of windows. Users interested in the number of windows in a specific room could acquire this information patiently traversing the room. Users who are not interested in finding out how many windows are in the room anyway, are not interested in receiving extra information in a passively manner. Therefore, in future work, all the windows will be represented by sonification at the same frequency. In addition, it has been discovered that users depend heavily on wall-following strategy to get familiar with the floor plans, which is in line with researches accomplished by Lahav and Mioduser (2008) in virtual environments and Jacobson (1993) in physical environments. In floor plan scenarios, conclusion can be drawn that, in general, the time needed by participants vary, according to the part of the stimuli. The areas of corners and doors, for example, were explored most intensively than others, particularly sonified wall sections were explored significantly more often. If there is more time to investigated, it is more likely to accomplish an improved reproduction of the floor plans. Finally, the accurate reproduction of window-wall proportions was not as good as expected. In the context of floor plans, participants could concentrate on other perspectives, such as the layout of the floor plans or the shape and size of rooms, rather than on the precise position and length of windows. In order to investigate whether it is possible for human users to achieve a more accurate estimation of sizes (such as proportion to the wall) and positions, further research has to be done.

3.4 Accurate reproduction of spatial knowledge with linear overlapping (Study III)

3.4.1 Introduction

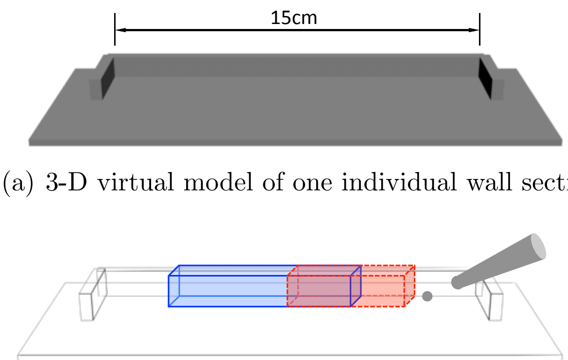
In Study II, since every single participant was able to reproduce all the windows on the correct wall, so it is safe to conclude that it was a reliable approach to represent spatial knowledge involving linear overlap relations with sonification in a virtual haptic environment in a qualitative manner. However, results also showed that the accuracy in the size and position reproduction of the windows was not satisfying. The hypothesis of explanations can be summarized as (a), caused by perceptual limits of using sonification to represent windows in virtual haptic floor plans, and (b), affected by intentional and attentional responding patterns of behavior. This means that users intending to acquire a floor plan may should mainly focus their attention on the layout of rooms and the apartment and only pay minor attention to the windows. To clarify these problems, this section reports on a study of perceptual and conceptual processing of linear overlap constellations in virtual haptic environments. In order to inspect how precise the size and position of linear spatial entities can be achieved by using a sonified haptic interface, a study of individual walls with varieties of overlap constellations was conducted. The investigated wall-window configurations were the same as in Study II. In this way, the influence of the complexity on virtual haptic environments was eliminated.

On the other hand, wall following and concurrent window following are not the only instances of spatial overlapping in 2.5-D floor plan explorations. In modern residence apartments, radiators are also commonly regarded as integral elements of internal surfaces of walls. It is worth noticing that radiators are often located below windows in the vertical dimension. These facts can easily produce overlapping between window following and radiator following emerging during wall following while exploring 2.5-D virtual haptic floor plans. An appropriate representation of spatial knowledge involving multiple overlaps remains to be implemented. So the second target of this study is to investigate the usability of representation for spatial overlaps among three different types of linear entities in haptic-audio environments. More specifically, I focus on (a) qualitative investigation on reproduction of overlap relations and (b) quantitative investigation on size and position reproduction of the linear entities.

3.4.2 Method

Stimuli

In order to keep the virtual haptic exploration free from complexities induced by complex virtual apartment environments, a virtual haptic model that only represents one individual wall section was implemented (see Fig. 3.10). The one-wall model was 15 cm long, with a boundary of 2 cm at both ends of the wall section, and it was placed on a solid horizontal plane. The wall and the two boundaries were 1 cm in high ensuring that wall-following exploration strategies were perfectly supported.



(a) 3-D virtual model of one individual wall section

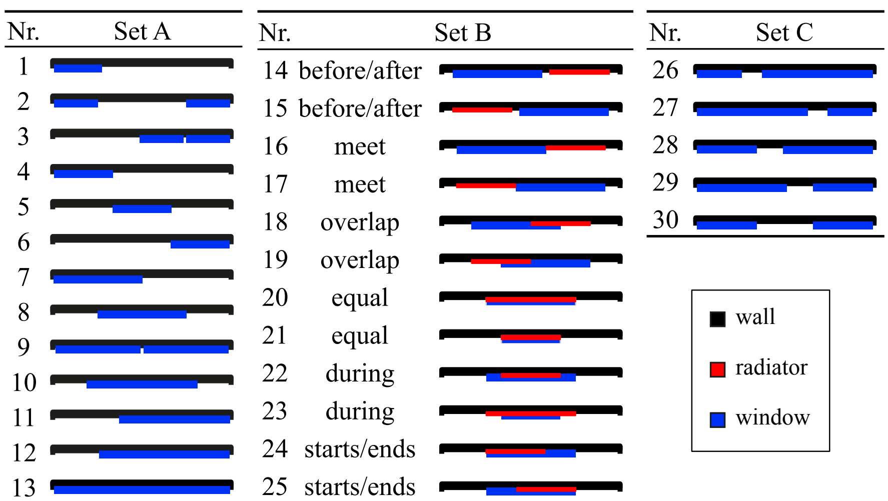
(b) The depiction of the one-wall virtual haptic model with other two different types of objects: the blue block (left) represents a window and the red one (right) represents a radiator

Figure 3.10: The one-wall virtual haptic model employed in the empirical experiment.

The spatial field that represents either a windows or a radiator is defined as a haptically non-perceivable cuboid with an intersection covering a square with sides lengths of 1 cm. All the sonification fields were seamlessly adhered to the walls. The moment the haptic interaction point (see the grey point depicted in Fig. 3.10(b)) enters the defined sonification field, the corresponding sonification resonates. Thus, invoking of the sonification can be carried out during the wall following, tolerating a reasonable amour of noise caused by hand movements, which was the proposed solution for the usability flaws discovered in Study II.

A repeated-measures study with 30 different virtual wall models was conducted (see Table 3.3). The virtual walls, numbered from 1 to 13 were called Set A. Virtual walls, numbered 17 to 25 were Set B. Numbers 26 to 30 were Set C. In Set A, the same window configurations that occurred in the complete apartment experiment were repeated. A quantitative between-group comparison of the performance concerning size and position reproduction of the windows was investigated. In Set B, all theoretically possible spatial relationships between windows and radiators were simulated. The window-radiator configurations in Set B were a genuine sonified haptic adaption of Allen's interval algebra for temporal internals (Allen, 1983; Rauh & Kulik, 2000). Set C was covered for comparison and balancing reasons. With these experimental stimuli, the usability of representing windows and radiators by representational multi-modality within auditory stimuli (harmonic tones with and without rhythm) was investigated, and we contributed towards discovering the influence on the accuracy of perception brought by the overlapping of the stimuli (J. Yu et al., 2013).

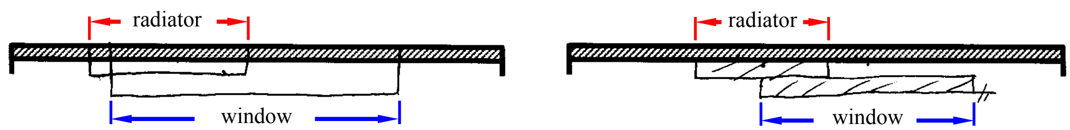
Table 3.3: Depiction of virtual wall stimuli employed in the experiment (the black color was used to represent the walls, the red for the radiators, and the blue for the windows).



Participant and procedure

25 participants (15 female, 10 male, mean age: 24.9 years, *SD*: 3.5 years) contributed to this empirical study. They were all sighted and right-handed university students with little or no experience with haptic force feedback devices. All the participants were blindfolded during the haptic exploration. The purpose was to investigate the usability of representational multi-modality of audio stimuli in representing spatial knowledge involving linear overlaps. The complexity of the virtual haptic model and the sonification stimuli in the experiment were also highly

limited. With these facts taken into consideration, the reported study is a human-computer interaction study based on a haptic-audio perception task. Thus, both visually impaired and sighted people were appropriate experiment participants.



(a) Sketch using frames to represent objects (b) Sketch using shadowed blocks to represent objects

Figure 3.11: Illustrations of various strategies employed by individual participants for representing windows and radiators in the empirical experiment, as well as the overlapping spatial relations between entities different types of wall-embedded facilities.

All the participants were first trained to operate the force feedback device and to deal with the experimental tasks for about half an hour. Then they were asked to explore 30 different and randomly arranged virtual wall models. There was no time limit for the exploration. After every exploration trial, the participants were given an answer sheet with an illustration of the wall measuring 10 cm. The experimental task was to sketch all the windows in blue and the radiators in red as accurately as they could (see Figure 3.11). The participants were aware that the width of the sonification filed was not relevant to this experiment. The test took 60 to 150 minutes per participant. There was a short break of 10 to 15 minutes halfway through each session. At the end, the participants were asked to fill in a questionnaire about what they think regarding the usability of this sonified haptic interface.

Evaluation

As sketching is considered to be a reliable data source of spatial cognition (Blades, 1990), the evaluation was based on the analyses of the sketches. The qualitative evaluation of recognising spatial relationships between windows and the radiators was achieved by analyzing the sketches from Set B. If the reviewers recognized the correct spatial relationships, the spatial relationships of the wall configurations were regarded as correctly recognized by the participants.

Quantitative evaluation was effected on the accuracy of size and position estimations of the entities. As exemplified by Figure 3.12, for the size estimation analysis of an entity AB, we measured the length of the sketched entity, which is

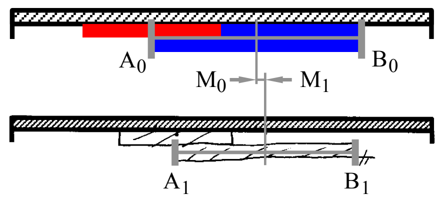


Figure 3.12: Illustration of sketch evaluation, where A_0 and B_0 are the end notes of the original stimuli; M_0 is the centre of the original stimuli. And A_1, B_1 and M_0 are the corresponding notes of sketches produced by participants.

the length of segment A_1B_1. The amount of error in size estimation was yielded by dividing the absolute value of the difference between the measured length A_1B_1 and the correct length A_0B_0, by the length of the printed wall (10 cm). Consequently, Equation 3.1 could compute the error in size estimation, and 3.2 could compute the amount of error in position estimation:

$$\Delta Size = \frac{|A_1B_1 - A_0B_0|}{10\ cm} \times 100\% \tag{3.1}$$

$$\Delta Position = \frac{|M_0M_1|}{10\ cm} \times 100\% \tag{3.2}$$

M_0 is the center of the entity in the original stimuli, and M_1 is the center of the sketched object.

3.4.3 Results

The qualitative investigations presented plausibility to represent linear overlaps with the support of sonification. In addition, according to the quantitative investigations, it was possible to identify how accurate size and position estimations of the overlapping objects actually are.

Qualitative investigation

The usability investigation was constrained to the qualitative correctness of the spatial relationship between one window and one radiator. According to the results, all participants were able to reproduce all the represented spatial relations correctly. These results strongly indicate that, on a qualitative level, spatial overlaps of linear entities can be represented by using representational multi-modality of audio stimuli. Again, it should be stated that using various rhythms is only one appropriate modality for auditory stimuli that could support representation of spatial overlaps in virtual haptic exploration, and that the existence of other (even better) representational modalities for representing overlapping spatial knowledge should not be excluded.

In the questionnaire, the participants reported that it was easy for them to understand and interact with the virtual force feedback device and the sonification. They were able to acquire the desired information respecting their individual wishes. In general, the experiment tasks were not challenging for them. However, most participants regarded overlapping windows and a radiators on wall configurations as the most challenging tasks.

Quantitative investigation

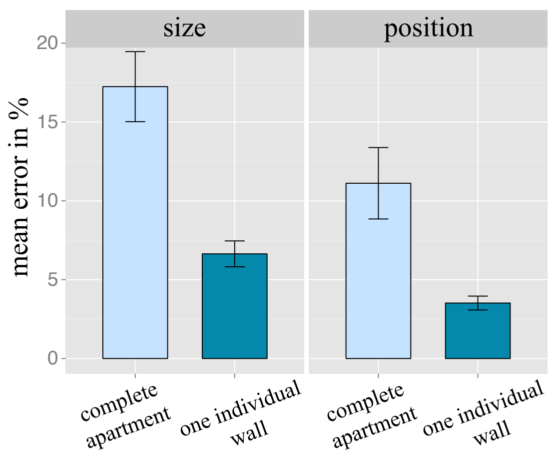


Figure 3.13: Comparison of error in size and position reproduction between exploring a complete apartment and a one-wall scenario. The difference in both size reproduction ($p < .001$) and position reproduction ($p < .001$) is statistically significant.

Apartment exploration vs. one-wall exploration. The data of Set A were compared with the data collected in Study II (J. Yu & Habel, 2012). As illustrated in Figure 3.13, in the one-wall scenario experiment, the error participants made significantly decreased regarding both size estimation ($mean_{apartment}$=17.24, $mean_{wall}$=6.63, $p < .001$) and positioning of windows in comparison to the apartment experiment ($mean_{apartment}$=11.07, $mean_{wall}$=3.48, $p < .001$). This result implied that the weak estimation performance in the apartment scenario was very likely due to the participants being focussed on further perspectives, such as the layout of the apartment or the sizes of every room, during the exploration.

Other factors on estimation accuracy. In this part, the quantitative analysis of accuracy of both size and position estimations is covered. First, in cases with windows and radiators overlapping, the amount of errors in size estimation was significantly larger than in configurations without overlaps ($mean_{overlap}$=9.75, $mean_{no\ overlap}$=7.00, $p < .01$, see Figure 3.14). The accuracy of positioning the objects was not significantly different ($mean_{overlap}$=4.59, $mean_{no\ overlap}$=4.21, $p >$ .05). Second, when two objects were on the wall, the accuracy of size estimations did not differ significantly ($mean_{one\ object}$=6.90, $mean_{two\ objects}$=7.03, $p > .05$), however, positioning accuracy decreased ($mean_{one\ object}$=3.42, $mean_{two\ objects}$=4.04, $p < .05$, see Figure 3.15).

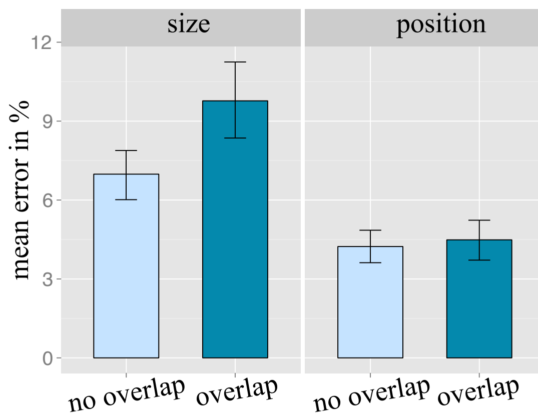


Figure 3.14: Within-group comparison of size estimation and positioning accuracy between stimuli involving overlap relations and non-overlap relations. The amount of mean errors in size reproduction is significantly different under these two conditions ($p < .01$), whereas the amount of mean errors in position reproduction is not ($p > .05$).

3.4.4 Discussion

Study III fulfills its targets in a satisfying manner. First of all, it has been proven that the accuracy regarding size and position reproduction after exploring virtual environment with sonification was significantly improved when the complexity of the environment was limited. The striking evidence suggests that poor performances regarding size and position reproduction in Study II were caused by the complexity of the floor plans.

Second, the results showed that sonification in virtual haptic environments is a suitable approach for representing spatial overlaps between walls and windows, and spatial overlaps involving even more types of entities such as walls, windows,

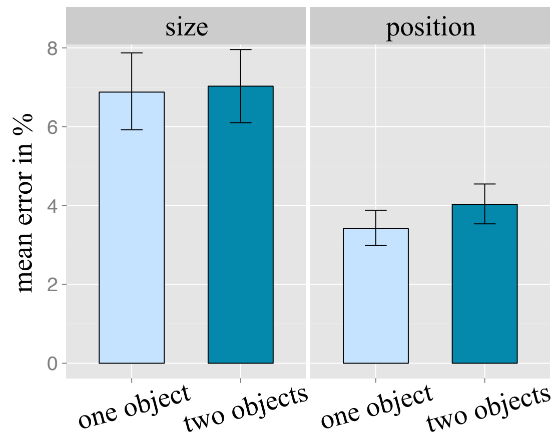


Figure 3.15: Within-group comparison of size estimation and positioning accuracy between stimuli involving one object or two objects. The amount of errors in size reproduction is not significantly different under these two conditions ($p > .05$). The mean value of errors in position reproductions with one object is significantly smaller than that with two objects ($p < .05$).

and radiators in 2.5-D floor plan scenarios. Even in complex constellations, linear spatial relations between objects were perfectly reproduced by participants, generally with a small amount of errors within a reasonable margin (about 10% for size reproduction, and about 4% for position reproduction).

Third, two predictors that have influenced accuracy reproductions of analog properties of the represented objects have been identified. It is more challenging to reproduce the size of sonified objects precisely when overlaps between two types of sonification take place. And the more objects represented on a specific wall section, the less accuracy regarding position reproduction is likely to be achieved.

Last but not least, according to the feedback shared by the participants in Study II, equally pitched signification for windows was employed in this study. In addition, a three-dimensional invoking space was implemented to substitute the invoking area on the floor ground in Study II.As participants gave positive comments, this implementation was used in the subsequent virtualization of this dissertation.

These results seem to be extendable to other types of overlaps, in particular overlap constellations in 2-D or 2.5-D spatial representations. With respect to the design of human-computer interfaces, the results point towards the necessity to respect the interrelationships of representational complexity and accuracy of information presented by sonification at an early stage in the design process.

3.5 Knowledge acquisition on floor plans with functional facilities (Study IV)

3.5.1 Introduction

When power-outlets are added into the inventory of sonified functional facilities in rooms, the possible number of different types of entities on a specific wall increases. The influence on the accuracy of fixed facility constellation reproductions caused by introducing sonified power-outlets should be investigated.

In this section, virtual haptic environments employed in the empirical study were set at room-scale in order to establish a complete three-step complexity hierarchy of virtual environments. Consequently, a cross comparison of reproduction performance respecting the complexity of virtual haptic environments was possible. The accuracy of size and position reproductions of functional facilities was analyzed quantitatively, and the correctness on spatial relations reproduction between entities was analyzed qualitatively.

3.5.2 Method

Participants

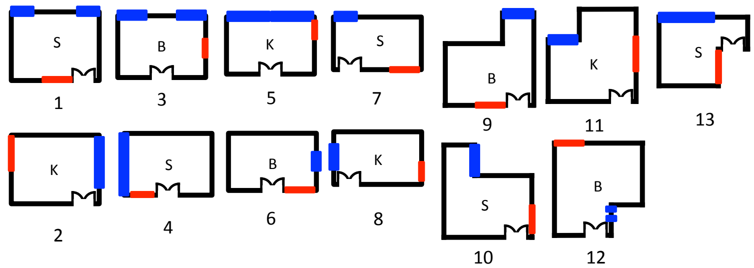
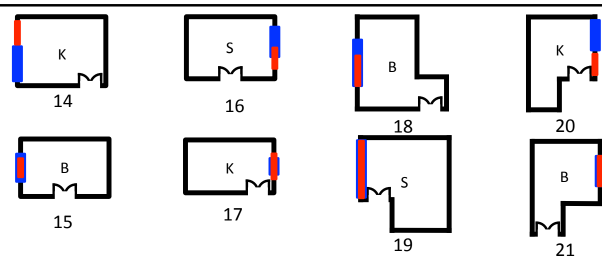
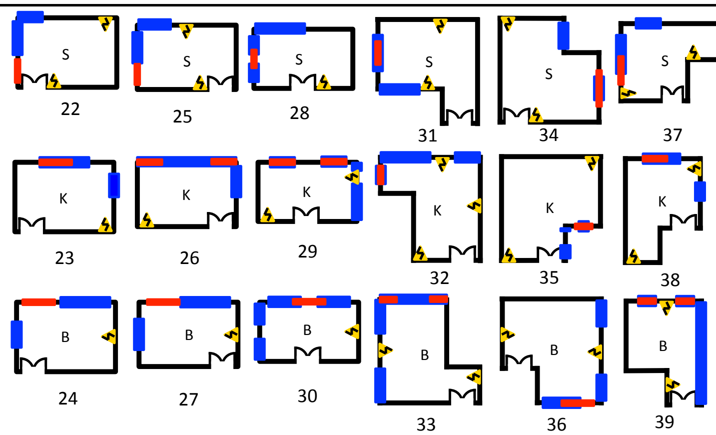
26 sighted participants (13 female, 13 male, mean age: 25.6 years, *SD*: 3.1 years) participated in this study. They all had no or very little experience regarding virtual haptic devices and haptic-sonified human-computer interfaces. All the participants used their prime hand for haptic exploration throughout the experiment. One participant was left-handed, but no significant differences were detected by the authors regarding the performance in comparison with right-handed participants. Participants were blindfolded while they explored the haptic-sonified room plans.

Stimuli

All the haptic-audio room plans were divided into three groups:

- Set A: Only one type of facility on one specific wall (either only window(s) or only radiator(s))
- Set B: Two types of facilities on one specific wall (window(s) and radiator(s))
- Set C: Three types of facilities on one specific wall (window(s), radiator(s), and power-outlet(s))

Table 3.4: Stimuli inventory of Study IV.

Grouping	Stimuli
Set A	
Set B	
Set C	

The size (window-wall proportions) in Set A were the same as those in the apartment scenario study (see Section 3.3.2 for detailed discussion). In Set B, there were no power-outlets in the rooms, but the windows and radiators were located on the same wall section. These window and radiator configurations composed all possible spatial relations between two linear entities, which represented a spatial adaption of Allen's interval relations, the same way as Set B did in the experiment of a one-wall scenario (see Section 3.4.2 for detailed discussion). Set C consisted of rooms with power-outlets. Besides, the rooms in Set C had one wall with both windows and radiators, and another wall with windows but no radiators. Walls with both windows and radiators had the same configurations as Set C in Study III (see Section 3.4.2 for detail discussion). Table 3.4 illustrates the stimuli inventory consisting in a total of 39 haptic-audio room plans with three different room types: sleeping rooms, kitchens, and bathrooms, marked S, K, and B correspondingly. The rooms have different shapes, either rectangular or L-shaped. In the rectangular rooms, the length-width ratio had four possible values, varying from 1:1.3 to 1:1.77.

Three varying combinations of different *concave-corner-edge proportions* and *negative space ratios* of L-shapes were employed:

- concave-corner-edge proportions: 1, negative space ratio: 0.16
- concave-corner-edge proportions: 1.14, negative space ratio: 0.22
- concave-corner-edge proportions: 2, negative space ratio: 0.27

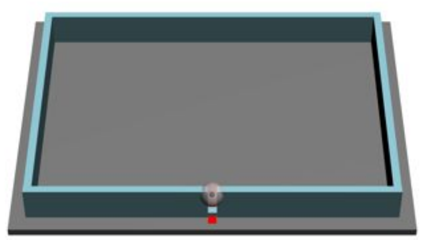


Figure 3.16: Example of the virtual haptic room plan models employed in Study IV.

The room plans had a size of around 500 square centimeters. The walls of the rooms were elevated by 2 cm. Solution B for virtualization of doors, as reported in in Section B.3, was employed. Users could feel the haptic-sonified room plans by touching them with a virtual haptic force feedback device. When the haptic interaction point entered the predefined space, verbal assistance resonated, communicating which type of room in being explored. In this study there were only three possible variants of room type: bathroom, sleeping-room, and kitchen. Windows, radiators, and power-outlets were not haptically perceivable, but represented by sonification. For windows, a continuous harmonic sonification at 261.63 Hz (musical note C4) was used and for radiators, it was aharmonic sound at 277.18 Hz (musical note C4#) with a salient rhythm, the same as in Study III (see Section 3.4.2 for detailed discussion). For the power-outlets, the sonification employed was a harmonic sound at 1046.5 Hz (musical note C6), lasting 300 milliseconds, and pausing milliseconds. Participants heard all the auditory input directly from the computer loudspeakers in order to avoid the discomfort of wearing headphones for a long period.

Procedure

The entire study consisted of three phases, namely the introduction phase, the experiment phase, and the interview phase. A session with one participant could take as long as two and a half hours. A repeated-measure design was employed. Each participant explored all 39 stimuli of the 3 groups.

In the introduction phase, the ethical guidelines produced by APA were introduced to the participants at the beginning, informing them that ethical concerns were taken into consideration by the conductors and the organizers. Secondly, a general background of the experiment was explained by the conductor. Then the participants learned how to operate the Omni and how to explore virtual haptic objects by going through three examples. A training session was included in the introduction phase. Stimuli No. 8, 16, and 36 were employed in the training section. Participants had unlimited time to explore haptic-audio room plans, and they were encouraged to raise questions or adderss the conductor in any manner. When the participant felt confident enough to produce a sketch of the room plan, the exploration was terminated. Then a sketch sheet was handed out, displaying a black square box measuring 10 cm. The participants were asked to sketched the walls in black, the windows in blue, and the radiators in red. There were no instructions regarding the color should be used for doors and power-outlets; they only had to be marked with recognizable symbols. Through these stimuli, participants were able to learn about the possible entities in the experiment and how to map the sonification of each entity type. The second purpose of the training session was to familiarize participants with the rules and procedures in the real experiment and to give them the chance to decide which symbols they would like to use for doors and power-outlet to reduce the learning effect on the collected data.

In the experiment phase, each participant ran through all the 39 stimuli in a random order. Throughout the experiment, the participants could ask for breaks at any time. In case that participants did not ask for breaks spontaneously, a mandatory break was taken halfway through the session.

Finally, a short interview with each participant was scheduled. In particular, a short demonstration of both the raised and indented variants of virtualization for furniture piece representation was presented to each participant and they were asked about their preferences. In addition, their general opinions and comments about the haptic-audio interface were discussed. It was also an opportunity to intensify the discussion about topics that emerged during the experiment.

3.5.3 Results

Qualitative analysis on the reproduction of power-outlets

Participants were able to reproduce 796 out of 832 total power-outlets (95.67%). The 36 missed power-outlets were committed by three participants. One participant did not mark up power-outlet in two rooms, each room containing two power-outlets. Another participant did not mark power-outlets in three rooms, each room also had two power-outlets. The remaining 26 missed cases belonged to the third participant, who only marked the power-outlets in three rooms. During the interview, these three participants confessed that they realized that they had totally forgotten to mark the power-outlets in a number of rooms. We regard the data of these three participants as outliers and have removed them from the data set.

For the power-outlets produced by the remaining 23 participants, who did not forgot to sketch power-outlets, two independent reviewers were asked to evaluate their position reproductions. Three different descriptions for the position of power-outlets were suggested to the reviewers:

- at the right / left end of the wall
- in the middle of the wall
- closely right / left to the door

If the reproduced position could be described in the same way as in the original stimuli, the reproduction was considered to be correct. On average, 28 out of 31 power-outlets per participant ($SD = 2.72$) were recognized as reproduced in the correct position on the wall.

These results supported the hypothesis that it was not challenging for users to recognize and reproduce sonified power-outlets when three types of functional facilities were represented by sonification.In addition, valuable position knowledge of sonified entities could be acquired.

Quantitative analysis on size reproduction of windows and radiators

Figure 3.17 illustrates the result of one-way repeated-measures ANOVA, supporting the hypothesis that the varing number of types of functional facilities had a significant effect on the amount of errors in size reproduction of the entities ($F(2, 1010) = 28.64$, $p < .001$, $r = .70$, which means that the variations in this variable explain 48.9% of the total variance in data). And the *Bonferroni ad-hoc test* showed that the differences between any pair of the conditions were all statistically significant ($p_{AB} < .001$, $p_{AC} < .001$, $p_{BC} < .01$).

However, *mixture distribution analysis* showed that there are two distributions in the entire data sample (Benaglia et al., 2009) that cannot be explained by the

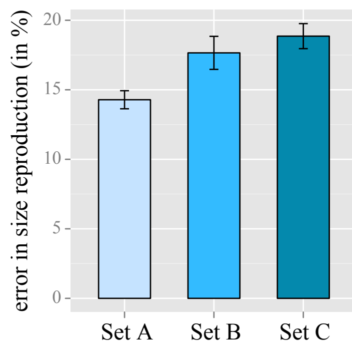


Figure 3.17: Summary of errors in size reproduction of wall-embedded facilities under different experimental conditions in Study IV. All the pair-wise differences were statistically significant.

Figure 3.18: Result of mixture distribution analyses. Two distributions were recognized, and marked with red and green line.

influence of constellation complexity (see Figure 3.18). This finding implies that aside from the predictor variable defined, other variables were also affecting the results.

Luckily, the study revealed that the time required for stimuli No. 26, 28, and 33 was above average (see Figure 3.19). As a matter of fact, stimuli No. 26 and 33 both have a wall with one window having start / end relation with two radiators. And No. 28 has a wall with one radiator having overlap relation with two windows. Also, No. 30 shows a similar constellation. The evidence suggested establishing a genuine variable called the *invading type* that described how entities of functional facilities invade one another's space. This variable also had three steps in valuation:

- *Non-invading*, which means any two entities of different type functional facilities did not occupy any part of the other at all.

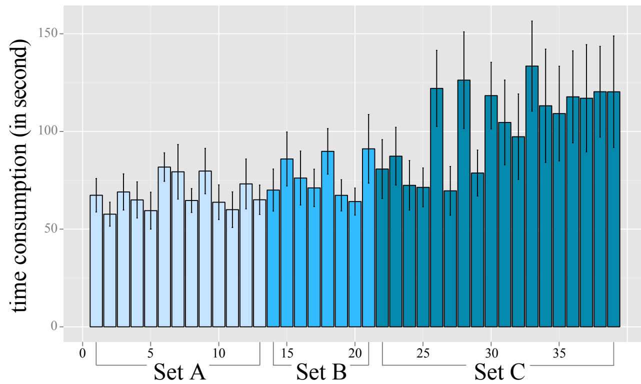
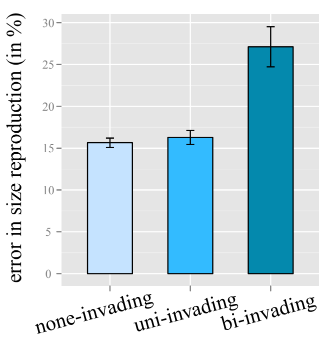
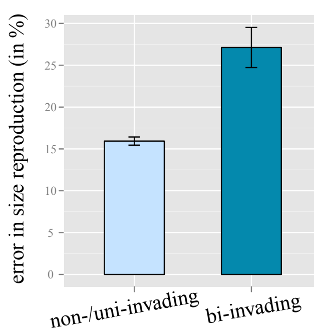


Figure 3.19: Time consumption of each room plan stimuli. No. 26, 28, 30, and 33 consume more time than other stimuli from the participants.

- *Uni-invading*, which means one entity of either type was overlapping one, and only one, entity of the other.
- *Bi-invading*, which means the functional space of a certain type of entity was invaded by two entities of the other type.



(a) Comparison among different invading conditions



(b) Two distributions in data

Figure 3.20: Errors in size reproduction when invading types is taken regarded as a predicator variable. The amount of errors in size reproduction under both non-invading conditions ($p < .001$) and uni-invading conditions ($p < .001$) is significantly smaller than under bi-invading conditions, while the mean values of errors in size reproductions under non-invading and uni-invading conditions do not significantly differ from each other ($p > .05$). Figure (b) illustrates the distribution of data when non-invading and uni-invading conditions are merged.

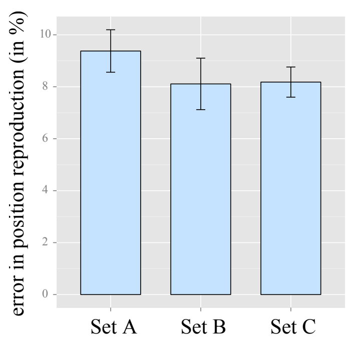
When the invading type was taken as a predictor variable, one-way repeated-measures ANOVA implied that there was a significant influence on the accuracy of size reproduction, $F(1,1011) = 177.4$, $p < .001$ and the effect size was larger than the miscellanea of functional facilities ($r = .92$, explaining 84.8% of the total variance). *Bonferroni ad-hoc tests* revealed that non-invading and uni-invading did not significantly differ from each other ($p > .05$) but both had significantly smaller errors than in *bi-invading* conditions ($p_{non-invading\ vs.\ bi-invading} < .001$, $p_{uni-invading\ vs.\ bi-invading} < .001$, see Figure 3.20(a)), which implied that we could safely merge the data of non-invading and uni-invading into one group (Figure 3.20(b)). This result is highly consistent with the outcome of mixture distribution analyses.

Quantitative analyses on position reproductions of windows and radiators

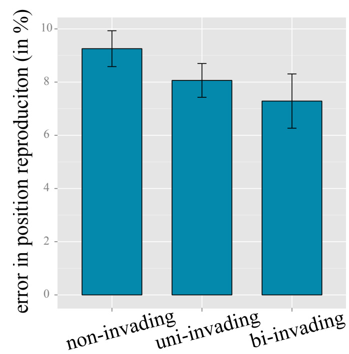
With respect to the amount of errors in position reproductions, ANOVA test showed that the number of types of functional facilities did not have significant influence on the accuracy of position reproductions (F(2,1010) = 1.48, $p > .05$) (see Figure 3.21(a)). Although invading types had the tendency of enlarging errors in position reproductions, the influence was not significant($F(2,1010) = 2.60$, $p > .05$) (see Figure 3.21(b)). These results implied that position reproductions of sonified functional facilities in room-acale virtual haptic environments were not significantly dependent on either the number of types of functional facilities or the complexity of spatial relation bared in the constellation.

Quantitative analysis on effects of complexity of virtual envrioment

The comparison of size and position reproductions across environments of different complexity was based on the same window configurations employed in Study II (apartment-scale), Set A in Study IV (room-scale), and Set A in Study III (one-wall). According to the results, the complexity of virtual environments affect on the accuracy of wall-embedded facility reproduction. ANOVA tests showed that the complexity of virtual environments had significant influence on the accuracy of both size reproduction ($F(2, 1996) = 915.6$, $p < .001$) and position reproductions ($F(2,1996) = 157.2$, $p < .001$) (see Figure 3.22). But the effect on size reproductions ($r = .70$, explaining 49.5% of total variance) was stronger than on position reproductions ($r = .40$, explaining 16.0% of total variance).



(a) Number of types of wall-embedded facilities configurations as predicator variable



(b) Invading types of wall-embedded facilities as predicator variable

Figure 3.21: Error in position reproduction with different predicator variables. ANOVA tests showed that these two predicators do not have statistically significant influence on the mean of error in position reproduction of wall-embedded facilities.

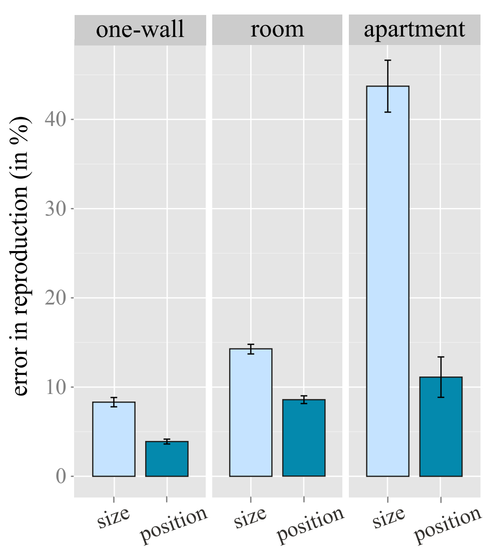
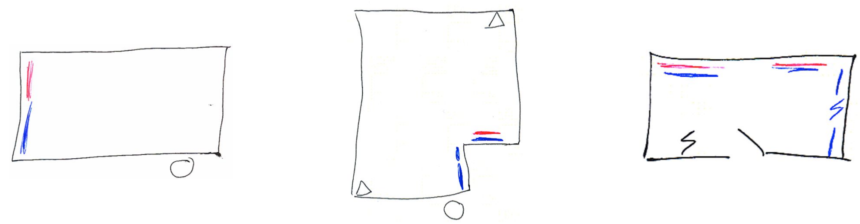


Figure 3.22: Cross environment comparison in size and position reproduction. Complexity of virtual environment had significant influence on accuracy of both size and position reproduction. And the influence on size reproduction was stronger than that on position reproduction.

Qualitative analysis on spatial relation reproduction

Two independent reviewers were asked to evaluate the linear spatial relations between entities in the sketches. The two reviewers agreed on 1011 sketches out of 1014. The three remaining negotiable sketches (Figure 3.23) were then evaluated by five other different reviewers. The intermediate and final results of the three negotiable sketches are given in Table 3.5.



(a) (b) (c)

Figure 3.23: Three negotiable sketches.

Table 3.5: Judgement of negotiable sketches.

		Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4	Reviewer 5	Final
Sketch (a)		meet	meet	meet	meet	before	meet
Sketch (b)		equal	equal	equal	equal	equal	equal
Sketch (c)	**left**	during	equal	during	during	during	during
	right	start	equal	during	start	start	start

Overall, 565 out of 832 (67.9%) relations were evaluated as correctly reproduced, which was not as good as 100% in the one-wall scenario. Out of the reproduced relations, two bigger clusters could be recognized. The participants did not recognize the relations *before/after*, and *meet* as significantly different from one another. Further, it was in line with the expectation of Allen's expectations (Allen, 1983) that *during/contain* and *start/end* belong to a bigger cluster.

The poor performance could be partly explained by the fact that the analyses of linear spatial relation reproductions were done qualitatively. But since the evaluation method was transparent to the participants, it could be possible that the participants reproduced the functional facilities were reproduced focussing on quantitative manner rather than on correctness of the qualitative spatial relations

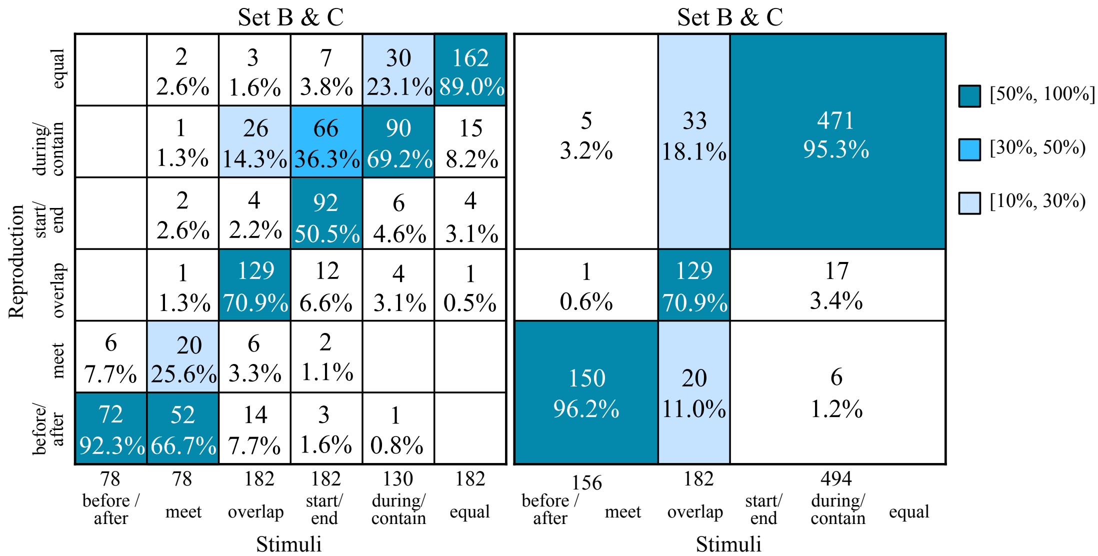


Figure 3.24: Summary of spatial relation reproductions of sonified functional facilities in haptic-audio room plans.

(a) (b) (c)

Figure 3.25: Examples of sketches with the ambiguity of spatial relations intended originally by the producers: blue lines represent windows and red lines represent radiators.

between two entities. Negotiable sketches could also be a relevant issue. For example, there are three window-radiator pairs, illustrated in Figure 3.25. The reproduced qualitative spatial relations could be recognized differently. Quantitatively, they could all be seen equally long, but in terms of qualitative spatial relations, case (a) is very likely to be evaluated as an *overlap* for linear spatial relations, case (b) could be regarded as *during/contain*, and case (c) as *start/end*. However, it would not be surprising if the producers of these sketches claimed that they all meant the same specific relation, which could be any one of the three mentioned above.

3.5.4 Discussion

Through the course and the analyses of this study, participants have been found able to recognize and reproduce sonified power-outlets with satisfying qualitative correctness in position reproductions. It was also not challenging to distinguish L-shaped room plans from rectangular ones. Participants were still able to reproduce the correct number of windows and radiators with a small, but significant, increase in the amount of errors made in size reproduction. However, introducing power-outlets did not significantly influenced the accuracy of position reproductions of windows and radiators. In addition, participants could reproduce L-shaped rooms correctly and in a qualitative manner.

One of the most interesting results of this study was that *bi-invading* constellations enlarged the amount of errors in size reproductions significantly, which was an extension of the conclusions drawn in Study III. These constellations also tend to enlarge the amount of errors in position reproductions, but the difference was not statistically significant. On the other hand, the complexity of virtual environments had large and significant effects on the accuracy of size reproductions and medium significant effects on the accuracy of position reproductions.

The linear spatial relations reproductions show that the results of the relations *before/after* and *meet* formed a bigger group, while *overlap*, *start/end*, *during/contain*, and *equal* shaped into another bigger group. As the results implied, when the space of one sonified object is totally contained in another object, more correctness in relation reproductions can be expected than in the case of two different objects partially overlapping each other's space.

In the interview section, after both raised variant and indented variant representing furniture pieces were presented, the majority thought that they were both user-friendly. However, 2 out of 26 participants preferred the elevation variant, which was in line with the visually impaired participants' opinion in the focus group study (see detailed discussion in Appendix C). Therefore, furniture pieces were decided to be implemented as elevations in subsequent research.

3.6 Summary

This chapter reports on the haptic-audio implementations representing linear overlap relations between different types of spatial objects and three empirical studies.

In study II, the same haptic-audio floor plans based on the same stimuli employed in study I were employed, and windows were represented by sonification. Invoking areas for sonification were defined on the floor along the bottom of wall. When the haptic interaction point makes contact with the invoking area during wall-following, the corresponding sonification resonates. A usability study has found out that it is not challenging to recognize the sonified section of a wall as a different object. Further, windows were always reproduced correctly in the corresponding walls. Moreover, compared to compared to Study I, in Study II participants achieved better performance sketching the floor plan and assigning the different rooms. However, the accuracy regarding size and position reproductions of sonified windows was not as good as expected. Further, two usability issues were identified. First, the invoking area did not tolerate hand movement noises, especially in vertical dimensions. Secondly, the same sonification was suggested to be assigned to all entities of the same type.

The hypothesis was that the complexity of virtual haptic environments affect accuracy regarding size and position reproductions of sonified windows. In order to investigate the accuracy human beings can achieve, the complexity of virtual haptic environments was reduced from entire floor plans to one individual wall in Study III. All the window configurations employed in Study I were repeated. Results showed that accuracy regarding both size and position reproduction was significantly improved in the one-wall scenario. And instead of plane invoking areas on the floor ground, three-dimensional invoking spaces were implemented as invoking spaces for sonification. As a result, noises of hand movement during haptic exploration no longer damaged the continuity of sonification sounds. Furthermore, the one-wall stimuli enabled users to acquire spatial knowledge of constellations involving multiple overlap relations when representational multi-modality of acoustic stimuli is applied in haptic-audio virtual environments. Stable harmonic sonification was employed as a representation for windows and radiators were made recognized by rhythm sonification. Participants were were able to reproduce size and position of sonified windows and radiators precisely with reasonably small amounts of errors. The occurrence of overlap relations between different types of sonified objects made size reproduction more challenging but did not have a significant influence on position reproductions. Constellations involving two objects made reproducing positions accurately more challenging but did not significantly influence influence proportion reproductions. These results support the argument that human beings are able to acquire and reproduce accurate linear analog properties of sonified objects during virtual haptic exploration.

In Study IV, an empirical study of haptic-audio interfaces was conducted to investigate the usability of representations of functional facilities in room-scale virtual haptic environments. Results show that it is not challenging to acquire spatial knowledge of three different types of functional facilities. Besides, being correct in reproductions of room types and room shapes, participants were even able to reproduce power-outlets as well as the spatial relations of window-radiator pairs in a qualitative manner. This study also bridges the gap of complexity levels, with respect to virtual haptic environments between Study II (apartment-scale) and Study III (one-wall). More solid evidence was collected, supporting the argument that the more complex the virtual haptic environment is, the less accuracy regarding position reproductions of sonified objects should be expected.

So far, a haptic-audio solution for representing spatial knowledge involving linear overlaps has been implemented and evaluated. As a next step, it makes senses to focus on the remaining expectations of the visually impaired, which are to make spatial knowledge of furniture pieces accessible in a non-visual manner.

Chapter 4

2-D overlapping between objects and regions

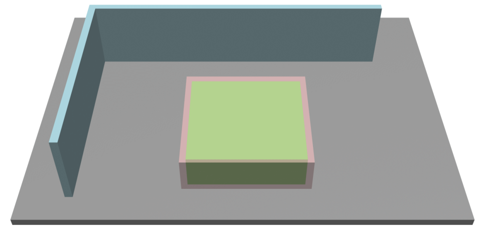
4.1 User expectations regarding spatial knowledge of furniture pieces

As elaborated by Montello (1993), human psychological space can be classified as rather global levels and rather local levels. Spatial knowledge of global level supports way-finding and route-planning tasks. Spatial knowledge of local level space supports finer manipulation of mobility and orientation, such as how to exactly make the next step so as to avoid obstacles. This fact influences the richness and amount of spatial knowledge required in each individual level of space. The indoor environment in the focus of this dissertation belongs to the rather local level. It is the contours of all the furniture pieces in a room that practically define the region which affords the mobility and orientation of people in the room (see Section C for detailed discussion). Therefore, it makes sense to further implement non-visually accessible haptic-audio floor plans.

4.2 Representation of furniture pieces

Based on the feedback collected from the focus group study (see Appendix C) and the questionnaire of Study IV, furniture pieces were implemented as solid raised blocks. The shape of the blocks various according to the specific furniture piece to be represented. Whereas all the furniture pieces have the uniformed height of 1 cm. So users can distinguish the edges of furniture from the walls by the heights. Besides, around all the furniture pieces there was a layer of space

(a) Segment of floor plan when furniture not displayed



(b) Segment of floor plan when furniture displayed

Figure 4.1: Example of haptic representation of furniture piece.

with thickness of 2 mm from the surface of each furniture pieces (see the red transparent space in Figure 4.1(b)). Inside this space, both the static and dynamic friction coefficients are set to be 0.2[1]Therefore, users could distinguish the contour of furniture pieces from walls according to the difference between the friction. The bricks only represent the position occupied by the furniture pieces. Such properties as stiffness, removable, foldable, spinnable, face of the doors, were not represented.

The proposed exploration strategy of furnished floor plan is that users first explore and get familiar with the unfurnished floor plan but with all the sonified functional facilities accessible. After users claim that they have acquired enough knowledge about the empty floor plan, furniture pieces will be displayed upon the existing floor plan. Then users can explore the floor plan for the second round, so as to update the mental model of the empty floor plan with reasonable efforts.

The switch-on and switch-off of the furniture display can be done by a single stoke on the keyboard. So both theoretically and practically, visually impaired users can decide and execute the switching on and off operation anytime they want. However, in order to control the empirical study under protocoled scenario, all the participants did the haptic exploration first in the empty floor plan then in the furnished floor plan in the following empirical studies.

The audio assistance for each furniture piece was also implemented in form of TTS audio files, telling users simply the name of the specific furniture piece. Upon the entry of the haptic interaction point into the verbal assistance invoking space of a furniture piece, the corresponding TTS file will fire out. As long as the haptic interaction point stays within the invoking space, the verbal assistant will not be repeated. There are two options to replay the verbal assistance. The first option is

[1]Although the just noticeable difference was expected to be 10% with physical objects, empirical trials implies that when the friction coefficients are greater than 20% users can detect the difference during blindfolded exploration easily. On the other hand, if the friction is too big, significant artifacts on virtual haptic exploration may be aroused.

to draw the haptic interaction point out of the invoking space and enter it again. The second is to replay it by clicking either of the two buttons on the stylus of Omni.

4.3 Knowledge acquisition in furnished floor plan (Study V Part 1)

4.3.1 Introduction

There are such doubts that whether such haptic-audio representation of furniture pieces can be used by visually impaired people, since when explored non-visually, empty floor plans can already be so challenging to learn about. So even though visually impaired users are interested, they may not be able to pay attention to the spatial knowledge of the furniture pieces. Now that practice would be one of the best approaches towards facts, the best answer may be given by an empirical study with real visually impaired participants.

However, visually impaired people are a relatively small group, which makes the conducting of empirical study with sufficient number of visually impaired people a challenging task. Fortunately, very strong support was contributed by Shanghai School for the Blind again, which made it possible to conduct intensive empirical study with visually impaired participants. The opportunity was precious. It required experimental designing that was free from obvious flaws. Software and hardware should be free from technical failures. And the experiment conductor should be familiar with the experimental designing and be able to conduct the study in a uniformed manner. All these requirements take a pilot study to fulfill in advance of the study with visually impaired participants. And such pilot study was at the same time a perfect training section for the experiment conductor.

The second challenge of empirical study with visually impaired participants in context of spatial knowledge acquisition would be the collection and analysis of the data. Since data collected from traditional sketching task done by visually impaired participant suffers dramatically from artifacts brought by limited sketching skills, more appropriate experimental tasks for visually impaired participants should be employed. Modeling task is one of the promising candidates for testing task for visually impaired people.

So the goal of this study was to serve as a plausibility investigation of the haptic-sonifed floor plan with furniture, so as to make sure the implementation of the system was free from failures, to train the study conductor, and to validate the reliability of the modeling test as appropriate testing method. At the same time, the results of sighted participants are the baseline data of a comparison with the results from visually impaired participants. The empirical study with visually impaired participants is reported in detail in Sectioin 4.4.

4.3.2 Validating test methods for visually impaired participants

Mental spatial model of sighted people can be reliably investigated through the sketches produced. But for visually impaired people, to find an appropriate testing method for each individual study has been a classic topic. It is also essential that the new testing method should be tested for reliability in advance to the real study (Kitchin & Blades, 2002; Newcombe, 1985). There are many successful examples in employment of modeling task and some psychologists claimed the natural consistency between different spatial knowledge reproduction tests, it is always strongly suggested to employ multiple parallel tests in every individual study, so as to access better insight of the mental spatial knowledge of participants (Janda, 1998; Urbina, 2011). So in Part 1 of this study (with sighted participants), except for the two reliable testing methods for sighted users, which are verbal description task and sketching task, modeling task was also employed. The consistence in results of these three tasks was evaluated. The outcome supported the argument that modeling task is a reliable testing method to investigate mental spatial model of floor plans. In Part 2, visually impaired participants would be asked to do verbal description task and the modeling task.

Verbal description task

Verbal description task is one of very few testing methods that is widely regarded as reliable approach to investigate mental spatial knowledge (Kitchin & Blades, 2002; Newcombe, 1985). Special advantage of this approach is that it is suitable for both visually impaired participants and sighted participants. In this study, verbal description was the first task after haptic exploration of the floor plans. To make the verbal description task the first one is helpful to investigate the raw mental spatial model of the participants. Since the on-line production of verbal description is not visually or haptically perceivable, participants are less likely to compose subsequent description under the influence of the context. This can keep participants less distracted by other perspectives of the description already given, while concentrating on transforming mental spatial model into external textual representation.

Participants were asked to give verbal description in their mother tongue. The descriptions were recorded and then transcribed. Agreement of two reviewers were reached upon the wording of the transcription. Participants were encouraged to give verbal descriptions as precise as possible. There was no limit on time duration, number of sentences, order in which objects are described, or substantial contents of the verbal description. Examples of two verbal descriptions are given in Table 4.1.

Table 4.1: Examples of verbal description produced by one sighted German participant and one sighted Chinese participant with English translation.

Original transcprit	English translation
Was ich gesehen habe ist dass untenlinks die Tür war. Dann geh ich die Wand links hoch. Und dann hab ich eine Steckdose. Hab im Rand drin einen Stuhl und davor den Tisch. Und dann hab ich an der hinteren Wand einen großen Schrank. Dann habe ich an der Ecke dieses Heizung-Fenster Komplexes gehabt, an der Seite. Genau, dann geht's hier die Ecke, dann hab ich da ein Sofa, einen Tisch, wieder ein Sofa. Jetzt obenrechts war auch eine Steckdoze, von zwei Steckdosen. (German)	What I have seen is that left below was the door. Then I go upward the wall on the left. And then I got a power-outlet. Inside the border was a chair and, in front of it, a table. And then on the beyond wall I got a big closet. Then I have the radiator-window constellation at the corner, on the margin. Yep, then here comes to the corner, then I got there a sofa, a table, und a sofa again. Now top right was a power-outlet as well, of the two of them.
这是一个办公室。入口进去左手边马上就是办公室左边的墙。沿着左边的墙走，快要走到上面的墙角的时候有一个电源。右边对称的地方也有一个电源。上面的那面墙上是一个很大的柜子。柜子前面，左手边是一个办公椅，办公椅前面是一个写字台。房间的右边的墙上从靠近下面的墙角开始是一扇窗，窗子里面还有一个暖气。房间的右下角有一个沙发，沙发前面有一个桌子，桌子前面还有一个沙发。(Chinese)	This is an office room. If you enter through the door and then turn left, you will immediately come to the left wall of the office. Go along the left wall, almost to the top-left corner, there is a power-outlet. Another power-outlet is located on the right wall which is ssymmetric to this one. There is a big closet on the upper wall. In front of the closet, on the left hand side, there is an office chair. In front of the chair, there is a desk. On the right wall, in the lower part, there is a window, with a radiator in it. In the right-bottom corner, there is a sofa. Infront of the sofa, there is a table. In front of the table, there is one more sofa.

Sketching task

Sketching task is supposed to be challenging to visually impaired people, since it demands many mental manipulation upon their mental spatial knowledge, such selecting, classifying, simplifying, and symbolizing their mental spatial knowledge, so as to compose a graphical projection of their spatial knowledge (Kitchin & Jacobson, 1997). In addition, it was proved that haptic stimuli can only contribute to egocentric representation (Morash et al., 2012), while the floor plan is a allocentric representation of the knowledge. The mental transformation from a egocentric representation to a allocentric representation is a skill with which not all visually impaired people are familiar. Therefore, the sketching ability of visually impaired people is not so strong as sighted people, and very few visually impaired people have experience in sketching tasks. This may bring more artifacts to the quality of sketches produced by visually impaired people. Although there are some successful examples of sketching task done by visually impaired people with equipments like haptic sketch-pads in case study (Downs & Stea, 1977; R. D. Jacobson, 1992), it does not necessarily guarantee the plausibility of sketching task in an empirical study where larger number of visually impaired participants are involved. In addition, according to the experience of the focus group study with visually impaired participants, during sketching task with haptic sketch-pads, participants had to feel the raised trace from time to time. As a direct consequence, palms and fingers of the participants can get considerably stained by traces of the writing instruments, e.g. oil from a ball pen or lead of a pencil. In spite of the fact that participants and their legal guardians did not complained upon this imperfection, sketching task was not considered as optimal testing method for visually impaired participants.

Mainly upon these two reasons stated above, sketching task was only done by sighted participants. The electronically stored sketches were evaluated by three independent reviewers. The outcome of the sketching task was compared with other two tasks.

Modeling task

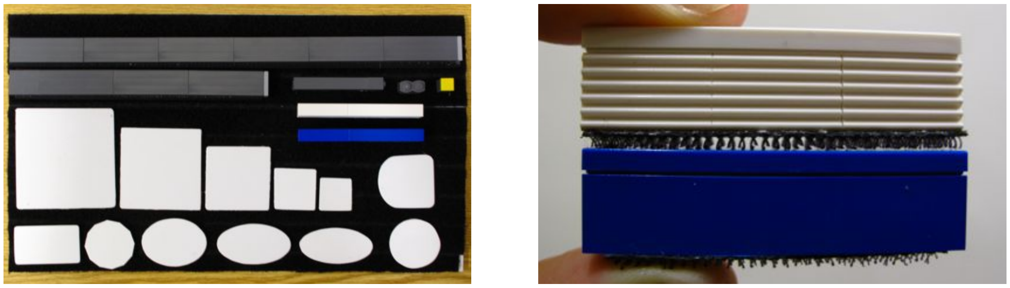
Modeling tasks, also named as reconstruction tasks, have been employed by psychologist, cognitive scientists, and computer scientists to investigate mental spatial model of visually impaired people for a long time. As described by Kitchin & Jacobson (1997), modeling task is different from sketching task in the way that the skillful manipulation acquired in knowledge transformation and drawing is minimized. Casey (1978) asked 10 congenitally blind participants to reproduce their campus with wooden blocks for buildings and strips for roads and paths. Passini &

Proulx (1988) conducted successful study which was to ask 15 congenitally totally blind participants to reproduce the route they have walked in university building, with magnetized wooden strips. Lahav & Mioduser (2008) also used modeling task to analyze mental spatial model of 31 participants of total blindness, which was acquired from a virtual haptic environment. Newcombe (1985) also commented that modeling task has the advantage of easy-to-understand, which is also a very important creiterium in the evaluation phase. All these facts imply that modeling task is suitable to be done by large number of visually impaired in empirical studies.

The modeling-kit used in the study consist of one plastic board, which was 30 cm x 17 cm large, and other 184 model pieces. The board, playing the role of the floor board of the floor plan, was covered with soft loop-side strips of Velcro hook-and-loop fasteners, which was not likely to hurt the fingers and palms of the participants during frequent haptic contact with bared hands. The other 184 plastic pieces were covered with Velcro hook-side strips at the bottom. So the placement of the model pieces was stable against normal haptic contact, but the possibility of replacement still remained. 56 of the 184 pieces were LEGO bricks, which include:

- thick grey strips, two were 30 cm, the other two were 17 cm long, which were used to define the external of the entire floor plan
- thin grey strips made up from unit modules of 1 cm in length, participants could extend the length of the strips by mounting more unit modules on either two ends of the brick. Altogether 20 pieces of unit modules were available
- blue strips with smooth surface for windows. There were six variations in length: 1.6 cm, 3.2 cm, 4.8 cm, 6.4 cm, 8 cm, and 9.6 cm. Two bricks for each length were available
- white strips with grooved surface for radiators. The same configuration for the window bricks was employed
- two special bricks for the doors, which looked like a combination of two eclipse cylinders
- six yellow unit module bricks for the power-outlets

The rest 128 plastic pieces were made from 2 mm thick polystyrene plastic board for furniture pieces in the modeling task. All the sharp edges and angles were polished off by sandpapers in advance, so as to avoid hurting the hands of participants, in particular hands of visually impaired participants. There were five different kinds of rectangular pieces, with aspect ratio of:



(a) Loop structure covered plastic board with various bricks and pieces

(b) LEGO bricks with hook structure at the bottom used for radiators (upper) and windows (lower)

Figure 4.2: Examples of modeling-kit used in modeling task.

- 1:1 (square)
- 1:1.33 (3:4)
- 1:414 (silver rectangles, or A4 rectangles)
- 1:1.618 (golden rectangles)
- 1:1.778 (16:9)

For each ratio, from large to small, there were five different sizes, each size was the area of 0.64 time of the former one. For every specific aspect ratio and size, there were always two pieces that were exactly the same. There were another 18 much slimmer rectangular plastic pieces. They had three different length (6 cm, 9 cm, and 12 cm) and three different width (1.3 cm, 1.6 cm, and 2 cm). For each specific length-width combination, two pieces were available. Besides, there were four kind of ellipses, with minor-major-axis-ratio of: 1:1(cycle), 1:1.33, 1:1.618, 1:1.778, 1:2. Similar to the rectangular pieces, each ratio had five different sizes and each size had two pieces. Finally, two sets of different shapes were also available:

- dodecagon pieces, but which had the same shape as the lamp in the floor plan stimuli, with incircle diameter of 1 cm, 1.5 cm, 2 cm, 2.5 cm, and 3 cm. Each size had 2 pieces.
- a modified shape based on a square, with three edges of the same length and the rest edge as a curve, so as to resemble the 2D contour of the armchair. The armchair pieces had the length of 1.5cm, 2 cm, 2.5 cm, 3 cm, and 3.5 cm for the straight edge which is opposite to the curved edge. For each size also 2 pieces were available.

There were no time limits for participants to finish the modeling task. The constructed models were photographed, then the photographs were evaluated by three independent reviewers.

4.3.3 Method

Participants

In the experimental design for sighted participant, three tasks were employed, namely verbal description task, sketching task, and modeling task. The verbal description task was always the first task after exploration of the haptic-audio floor plans. In order to balance the consequence of the sketching task and the modeling task, two different groups of sighted participants were invited to this study. The task consequence of these two groups is illustrated by Table 4.2. Group *GS* consist of eight German sighted university participants from Hamburg (5 female, 3 male, mean age: 24 years, *SD*: 1.2 years), and Group *CS* consist of eight Chinese sighted university participants from Shanghai (2 female, 6 male, mean age: 23.9 years, *SD*: 1.1 years). In Hamburg, before the data of the eight participants were collected, three pilots study were conducted, nevertheless the data was not employed in the analysis. No pilot study with sighted participants was conducted in Shanghai, as it was considered as not necessary for the very same study conductor. The participants in Hamburg received either course credits, or monetary compensation for their contribution, whereas all the participants in Shanghai received monetary compensation.

Table 4.2: Different task consequences of two sighted groups.

Task concdquence	Group	
	SG	SC
1st	verbal description	verbal description
2nd	skethcing	modeling
3rd	modeling	sketching

Stimuli and procedure

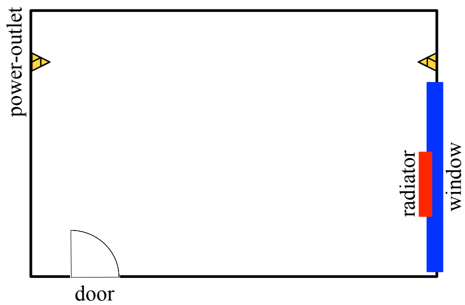
Throughout the entire study procedure, all the participants from both groups received instructions in their mother tongue, so was the verbal assistance employed by the haptic-audio floor plan. Table 4.3 shows the content of verbal assistances employed in the study in German and Chinese, with English translation. Each participant took part in all four sections of the experiment, namely introduction section, training section, experiment section, and finally interview section.

Table 4.3: Translation of all the verbal assistances employed in Study V.

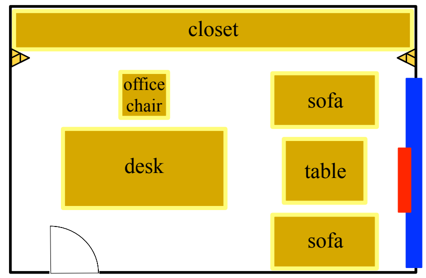
Nr.	German	Chinese	English
1	Bett	床	bed
2	Badewanne	浴缸	bathtub
3	Fenster	窗口	window
4	Heizkörper	暖气	radiator
5	Lampe	灯	lamp
6	Nachtschrank	床头柜	night stand
7	Schrank	壁橱	closet
8	Schreibstuhl	办公椅	office chair
9	Schreibtisch	办公桌	desk
10	Sessel	扶手椅	armchair
11	Sofa	沙发	sofa
12	Steckdose	电源插座	power-outlet
13	Tisch	桌子	table
14	Waschbecken	水槽	sink
15	WC	厕所	wc

In the introduction section, participants received the general insight of the study and had the chance to get familiar with the Omni device through three examples, which was similar to the introduction section arranged for the earlier empirical studies. The introduction section lasted 20 to 30 minutes.

In the training section, participants explored the haptic-audio room plan of an office. The room plan was first explored as empty room. In the empty room plan, only functional facilities were displayed. When the participants claimed that they had received sufficient knowledge about the empty office, the furniture pieces were displayed (see Figure 4.3). During the exploration of the haptic-audio room plan, sighted participants were asked to ware blindfolds, and they were encouraged to ask questions and report anything that was uncomfortable. There was no time limits for the exploration of both the empty room plan and the furnished room plan. After participants finished exploration phase, they took three tasks in the consequence presented by Table 4.2. This brought the participants the benefit that they were already familiar with the tasks before the real experiment section. The training section usually lasted 20 minutes. When the training section was finished, participants could take a break of 10 to 15 minutes.

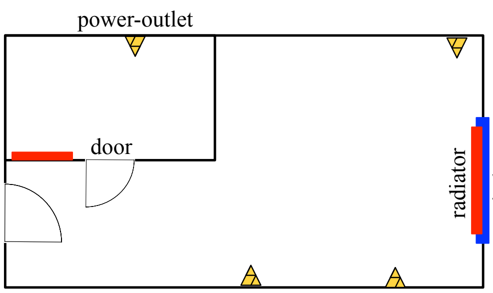


(a) Depiction for empty office room plan with functional facilities

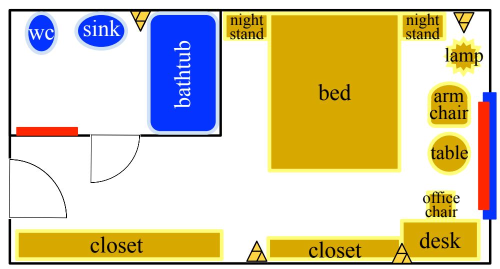


(b) Depiction for office room plan with furniture

Figure 4.3: Depictions for haptic-audio stimuli employed in the training section.



(a) Depiction for empty hotel floor plan with functional facilities



(b) Depiction for hotel floor plan with furniture

Figure 4.4: Depictions for haptic-audio stimuli employed in the experiment section.

In the experiment section, participants explored a haptic-sonifed floor plan of a standard hotel room. Similar to the scenario as in the training section, empty floor plan was initially explored, then furniture were displayed. Subsequently, participants went through exactly the same tasks as in the training section. However, during the experiment section, participants could not received any help from the experiment conductor, unless technical error occurred. Stimuli for the hotel room are depicted by Figure 4.4. This section last about 20 minutes.

Finally in the interview section, a feedback questionnaire was filled by participants. Participants were encouraged to share their comments and remarks upon the haptic-audio interface, as well as the experience of participating the study. Emerging topics were also discussed.

4.3.4 Results

Group *GS* (German sighted)

The sighted german group achieved good performance in all three reproduction tasks in both training section and experiment section. The mean accuracy of the individual tasks stayed around 80 percent. In the training section, 71.9% of the objects in the office room plan was correctly reproduced in all three tasks. In the experiment section, 64.9% of the objects in the hotel floor plan were correctly reproduced in all three tasks.

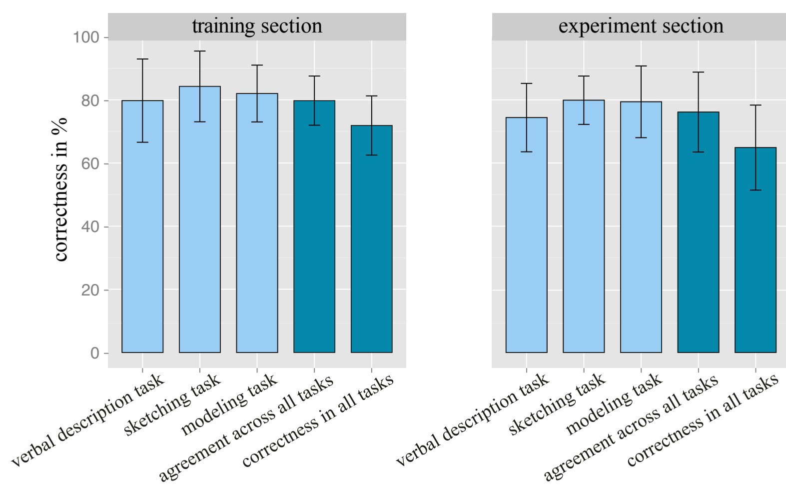


Figure 4.5: Correctness in amount of objects reproduced by German sighted participants. Performance of German sighted participants between the training section and experiment section was not significantly different ($p > .05$).

More importantly, it was discovered that in the training section on average 79.6% of object reproduction was consistent across all three tasks, and 77.8% of object reproduction was consistent across tasks in experiment section. No significant differences were found between accuracy in object reproduction of any two tasks in both training section and experiment section. And no significant difference in outcome of each individual testing task was found between the training section and experiment section. Although the mean values of consistency and correctness across all the three tasks in experiment section were lower than those in training section, the differences were also not statistically significant ($p > .05$, see Figure 4.5). With these facts, stable level of performance by sighted german participants is self-explaining.

More specifically, in the training section, the correctness in verbal description task was significantly correlated with correctness in the sketching task, $\tau_{t1} = .63$, p

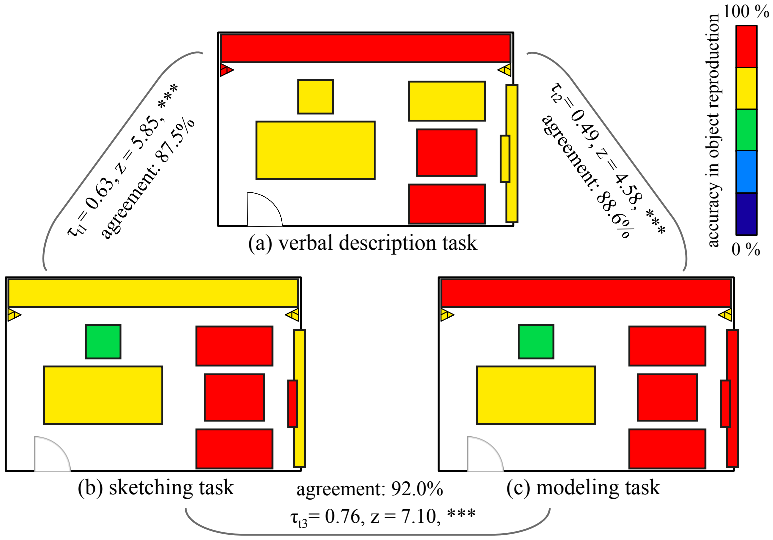


Figure 4.6: Correlation coefficients between performance of three different reproduction tasks done by German sighted participants in the training section. The probability of reproduction of furniture pieces was significantly correlated between any two of the three tasks in the training section (*** means $p < .001$).

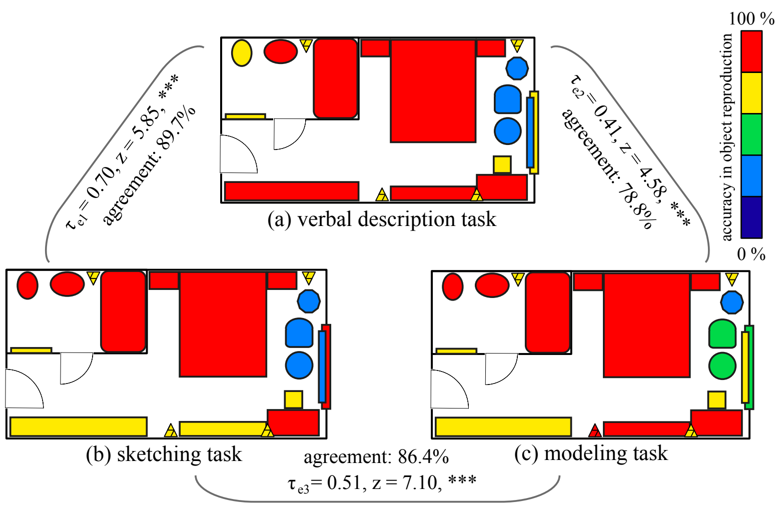


Figure 4.7: Correlation coefficients between performance of three different reproduction tasks done by German sighted participants in the experiment section. The probability of reproduction of furniture pieces was significantly correlated between any two of the three tasks in the experiment section (*** means $p < .001$).

$< .001$. The correctness in the verbal description task was significantly correlated with correctness in the modeling task, $\tau_{t2} = .49$, $p < .001$. And the correctness in the sketching task was significantly correlated with correctness in the modeling task, $\tau_{t3} = .76$, $p < .001$ (see Figure 4.6). Similarly, in the experiment section, the correctness in the verbal description task was significantly correlated with correctness in the sketching task, $\tau_{e1} = .70$, $p < .001$. The correctness in the verbal description task was significantly correlated with correctness in the modeling task, $\tau_{e2} = .41$, $p < .001$. And the correctness in the sketching task was significantly correlated with correctness in the modeling task, $\tau_{e3} = .51$, $p < .001$ (see Figure 4.7). Besides, with Bonferroni add-hoc test we discovered that the correlation between the correctness in any two tasks was not significantly different over the two sections, $p > .05$, which shows the stable consistence in the outcomes of these three tasks, and implies that the modeling task is another reliable approach to investigate mental spatial models of users.

The answers to the questionnaire are summarized in Table 4.4. The answers was suggested to participants in 5-point *Likert scale*, where 1 meant *strongly agree* and 5 meant *strongly disagree*.

First of all, the knowledge mapping between audio assistance and the representation of the objects in the floor plan was not challenging for the participants to get familiar with (No. 1). Participants reported that they were quite interested in the information about the furniture (No. 16), and that the verbal assistance was very helpful for them to identify each specific furniture piece (No. 6), but it was challenging for them to figure out the shape, aspect ratio, size, and position of the furniture (No. 2-5). With regard to the functional facilities, the information about the windows, the radiators, and the power-outlets were equally interesting to the participants (No. 13-15). To figure out the position of the windows and radiators were both not very challenging (No. 7, 9), but it was a little bit more demanding to estimate the length of the these two types of objects (No. 8, 10), however this difference was not statistically significant ($p > .05$). From the results of question No. 11 and 12 we can see that participants found it easier to locate the doors than the power-outlets ($p < .01$). The participants agreed that to explore the empty floor plan first, and then have the furniture displayed was a good strategy (No. 19). The results of questions No. 20 and 21 imply that the participants tended to be more confident in their performance in the molding task than in the sketching task. However the difference was not statistically significant ($p > .05$). And last but not least, on average the participants would rather strongly recommend this interface to visually impaired people (No. 18).

Table 4.4: Summary of answers to the questionnaire given by German sighted participants (1 meant *strongly agree* and 5 meant *strongly disagree*).

Nr.	Question / Statement	Answers	Mean	SD
1.	It was challenging for you to get familiar with the mapping between different sound and entities.	3, 5, 4, 3, 2, 2, 2, 4,	3.13	1.13
2.	It was challenging to figure out the shape of the furniture.	1, 4, 1, 2, 2, 2, 1, 4,	2.13	1.25
3.	It was challenging to figure out the horizontal and vertical proportion of the furniture.	2, 3, 3, 4, 2, 2, 2, 2,	2.50	0.76
4.	It was challenging to figure out the size of the furniture.	1, 3, 3, 2, 1, 2, 1, 3,	2.00	0.93
5.	It was challenging to figure out the position of the furniture.	1, 2, 2, 2, 2, 2, 3, 3,	2.13	0.64
6.	The verbal assistant telling the name of furniture was helpful.	1, 1, 1, 1, 1, 2, 2, 1,	1.25	0.46
7.	It was challenging to estimate the position of the windows.	1, 4, 4, 4, 2, 2, 4, 5,	3.25	1.39
8.	It was challenging to estimate the length of the windows.	1, 4, 3, 3, 1, 2, 2, 4,	2.50	1.20
9.	It was challenging it was to estimate the position of the radiators.	2, 4, 2, 4, 3, 2, 4, 5,	3.25	1.16
10.	It was challenging to estimate the length of the radiators.	1, 4, 2, 3, 3, 2, 2, 4,	2.63	1.06
11.	It was challenging to figure out the position of the power-outlets.	2, 5, 4, 4, 2, 2, 4, 5,	3.50	1.31
12.	It was challenging was to figure out the position of the doors.	4, 5, 5, 5, 3, 4, 4, 5,	4.38	0.77
13.	It was important for you, to know about the information of the windows.	1, 3, 2, 4, 1, 2, 3, 3,	2.38	1.06
14.	It was important for you, to know about the information of the radiators.	3, 3, 2, 2, 3, 2, 2, 2,	2.38	0.52
15.	I was important is for you, to know about the information of the power-outlet.	3, 3, 2, 2, 1, 4, 2, 2,	2.38	0.92
16.	It is important to you, to know about the information of the furniture pieces.	1, 3, 1, 1, 1, 3, 1, 1,	1.50	0.93
17.	The experience of using this interface was pleasant.	3, 3, 1, 3, 1, 2, 2, 2,	2.13	0.83
18.	You would recommend this interface to someone else who are blind or visually impaired.	1, 1, 1, 2, 2, 2, 1, 1,	1.38	0.52
19.	The order of empty display and furnished display of the floor plan is organized in a helpful way.	1, 1, 1, 1, 2, 2, 2, 1,	1.38	0.52
20.	You are confident in your performance in the sketch task.	5, 3, 4, 3, 3, 5, 3, 3,	3.63	0.92
21.	You are confident in your performance in the modeling task.	3, 2, 4, 3, 2, 5, 2, 2,	2.88	1.13

Group *CS* (Chinese sighted)

Chinese sighted participants had good performance as well. In the training section, participants reproduced 85.4 % of all the objects in the office room plan, 89.8 % in the modeling task, and 92.1 % in the sketching task. In the experiment section, 81.4 % of the objects were correctly reproduced in the verbal description task, 77.8 % in the modeling task, and 79.4 % in the sketching task. With regard to agreement across tasks, in the training section, 84.3 % of reproduction agreement was achieved across tasks and 79.8 % of the objects were correctly reproduced in all three tasks. And in the experiment section, 85.4 % of across-task agreement was reached and 73.1 % of the reproduction was correct in all three tasks.

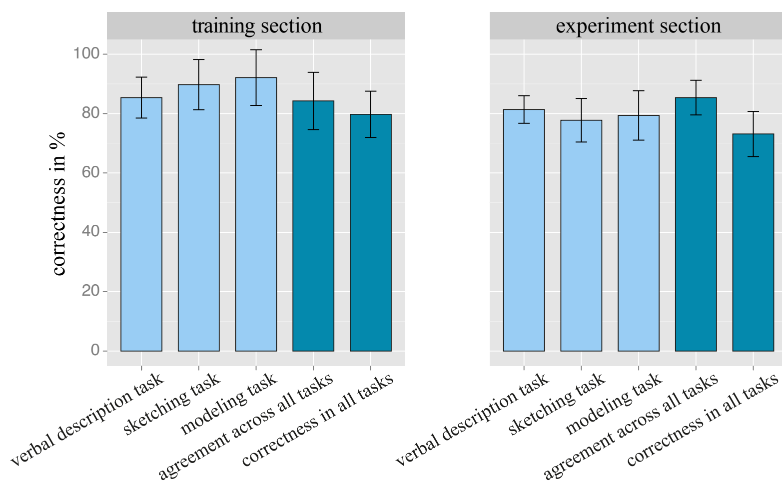


Figure 4.8: Correctness in amount of objects reproduced by Chinese sighted participants. Performances in sketching task ($p < .05$) and modeling task ($p < .05$) in the training section were significantly better rated than those in the experiment section. The difference in agreement across all tasks was not statistically significant ($p > .05$).

In training section, participants had better performance in both modeling task ($p < .05$) and sketching task ($p < .05$) than in the experiment section. However, the agreement in outcome of the all the tasks were not significantly different ($p > .05$), which showed the robustness of the consistence among these three tasks in investigating mental spatial models of different levels of complexity (see Figure 4.8).

Detailed correlation coefficients and agreement between every two tasks are illustrated in Figure 4.9 and Figure 4.10. The correlation coefficients of every individual task had not changed significantly over the two sections ($p > .05$).

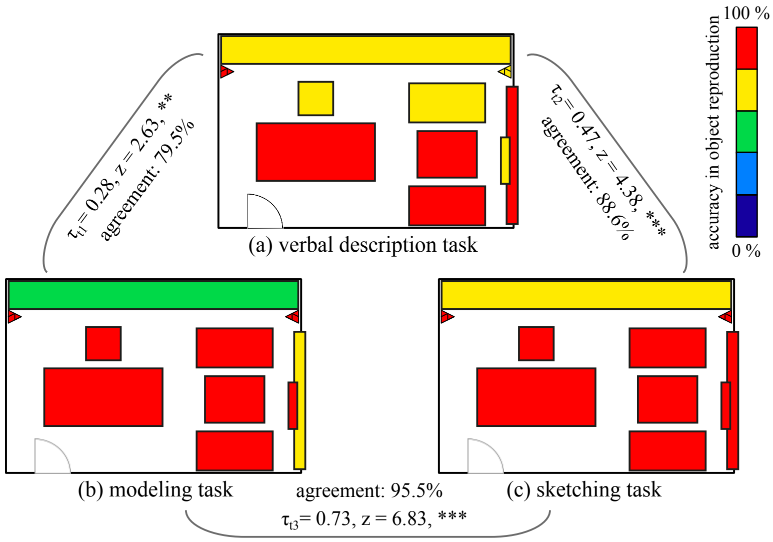


Figure 4.9: Correlation coefficients between performance of three different reproduction tasks done by Chinese sighted participants in training section. The probability of reproduction of furniture pieces was significantly correlated between any two of the three tasks in the training section (** means $p < .01$, *** means $p < .001$).

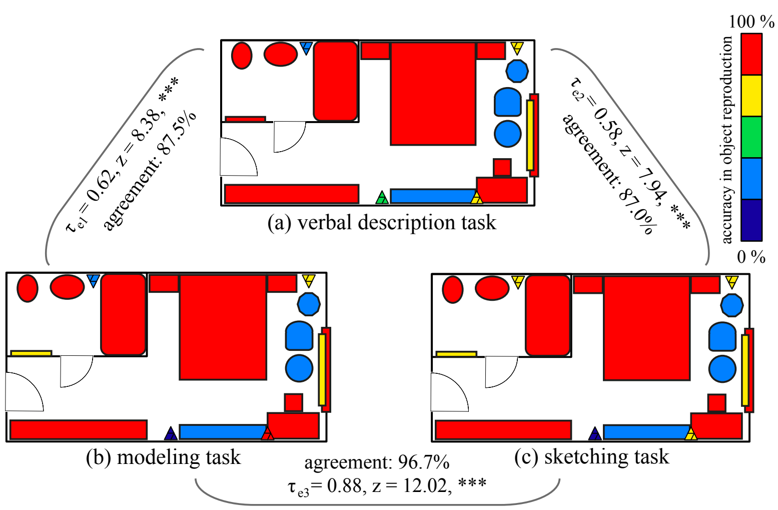


Figure 4.10: Correlation coefficients between performance of three different reproduction tasks done by Chinese sighted participants in the experiment section. The probability of reproduction of furniture pieces was significantly correlated between any two of the three tasks in the experiment section (*** means $p < .001$).

The answers to the questionnaire given by Chinese sighted participants are summarized in Table 4.5. It was not challenging for the participants to get familiar with the mapping between sonification and representations of the functional facilities (No. 1). They were interested in the information about furniture (No. 16). The verbal assistant was considered to be very helpful (No. 6). The level of challenging of identifying various properties of the furniture pieces did not differ significantly (No. 2-5). The information of the radiators was regarded not so important to the participants as the windows (No. 13, 14, $p < .01$). And the positions of windows were easier to estimate than the length of them (No. 7, 8, $p < .05$). Similar situation occurred with radiators (No. 9, 10, $p < .01$). Information about power-outlet was important to the participants (No. 15). On average, the participants found it was more challenging to locate the powet-outlets than to locate the doors, however the difference was not statistically significant (No. 11, 12, $p > .05$). All the participants though it was good to first explore the empty floor plan then the furnished display. With respect to their performance in the tasks, they were more confident in the sketching task than the modeling task (No. 20, 21, $p < .01$). In general, the participants claimed that it was a pleasant experience to use the interface (No. 17). And they were very likely to recommend this interface to people with visual impairments (No. 18).

4.3.5 Discussion

Through empirical results of two parallel groups of sighted participants from Germany and China, no obvious usability flaws were discovered, and no technical failure took place. The outcome of the modeling task replicated the outcome of the verbal description task and the sketching task, which was supported by the large correlation coefficients and high agreement values in both simple floor plan employed in the training section and rather complex floor plan in the experiment section. Also, the validation of the modeling task was proved to be robust for participants with different language and culture background, which was another necessary condition for the interface to be tested with students at Shanghai School for the Blind. One substantial instance of cultural difference was shown by the opinion over radiators reported in the questionnaire. Information about radiators was significantly more important to the German participants than to the Chinese participants. As radiators are standard indoor functional facilities in Germany, while they are extremely rare in south China, where Shanghai is located. However, no influence was discovered on reproduction correctness of the sonified radiators between these two groups.

Besides, there were some interesting discoveries from these two groups. In the experimental designing aspect, the only difference in study conduct between Group

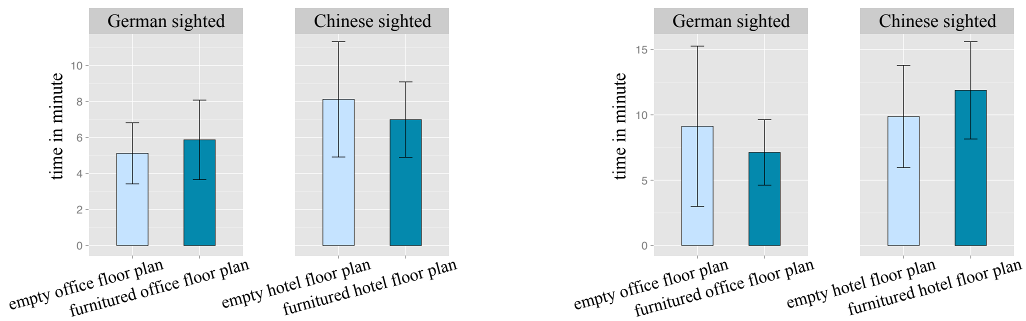
Table 4.5: Summary of answers to the questionnaire given by Chinese sighted participants (1 meat *totally agree*, and 5 meant *totally disagree*).

Nr.	Question / Statement	Answers	Mean	SD
1.	It was challenging for you to get familiar with the mapping between different sound and entities.	3, 3, 3, 4, 2, 4, 3, 4,	3.25	0.71
2.	It was challenging to figure out the shape of the furniture.	2, 3, 3, 2, 3, 4, 4, 4,	3.13	0.83
3.	It was challenging to figure out the horizontal and vertical proportion of thefurniture.	3, 3, 3, 3, 2, 4, 3, 3,	3.00	0.53
4.	It was challenging to figure out the size of the furniture.	4, 3, 4, 3, 3, 4, 4, 3,	3.50	0.53
5.	It was challenging to figure out the position of the furniture.	4, 3, 4, 3, 3, 3, 3, 3,	3.25	0.46
6.	The verbal assistant telling the name of furniture was helpful.	1, 2, 1, 1, 1, 1, 1, 1,	1.13	0.53
7.	It was challenging to estimate the position of the windows.	4, 3, 3, 4, 5, 5, 4, 5,	4.13	0.83
8.	It was challenging to estimate the length of the windows.	3, 2, 3, 3, 3, 4, 4, 3,	3.13	0.64
9.	It was challenging it was to estimate the position of the radiators.	4, 3, 3, 3, 3, 4, 4, 4,	3.50	0.53
10.	It was challenging to estimate the length of the radiators.	4, 1, 3, 3, 2, 3, 3, 2,	2.63	0.92
11.	It was challenging to figure out the position of the power-outlets.	3, 3, 4, 4, 3, 4, 5, 5,	3.88	0.83
12.	It was challenging was to figure out the position of the doors.	5, 3, 5, 5, 4, 5, 4, 3,	4.25	0.89
13.	It was important for you, to know about the information of the windows.	2, 3, 2, 2, 2, 1, 1, 3,	2.00	0.76
14.	It was important for you, to know about the information of the radiators.	3, 3, 3, 3, 4, 4, 4, 2,	3.25	0.71
15.	I was important is for you, to know about the information of the power-outlet.	1, 3, 2, 1, 3, 3, 3, 2,	2.25	0.89
16.	It is important to you, to know about the information of the furniture pieces.	2, 3, 2, 3, 3, 2, 3, 2,	2.50	0.53
17.	The experience of using this interface was pleasant.	3, 3, 1, 3, 1, 2, 2, 2,	2.13	0.83
18.	You would recommend this interface to someone else who are blind or visually impaired.	1, 2, 2, 1, 1, 2, 1, 2,	1.50	0.53
19.	The order of empty display and furnished display of the floor plan is organized in a helpful way.	1, 1, 2, 1, 1, 2, 2, 1,	1.38	0.52
20.	You are confident in your performance in the sketch task.	2, 2, 2, 3, 2, 1, 2, 3,	2.13	0.64
21.	You are confident in your performance in the modeling task.	4, 3, 3, 3, 4, 4, 2, 4,	3.25	0.71

GS and Group *CS* was the order of the testing tasks. In the experiment section, the correlation between the sketching task and the modeling task of Group *CS* was significantly stronger than that of Group *GS* ($z = 2.88$, $p < .01$). The level of confident in the performance in the modeling task of Group *CS* was not significantly higher than Group *GS*. And Group *CS* was considerably more confident than Group *GS* in the sketching task, and the difference was statistically significant ($p < .01$), which could be an effect brought by the difference in task order. During the modeling task, the model under construction was rendering visual input to the participants. Since the modeling task carries aiding information (although minimized), participants could take the model as supportive clues to the original stimuli. As a result, it was possible that participants from Group *CS* either confirm, or modify/adjust their mental spatial model established through haptic-audio exploration depending on the models constructed by themselves. After that, the sketching task could be transformed from producing a sketch of the indoor environment perceived from the haptic-audio interface into producing a sketch of the indoor environment which could be represented by the model constructed and visually observed one moment ago. This may be the cause of the large correlation value between these two tasks done by Group *CS*. And it may also be the origin of the confidence in their performance of the sketching task. This could also partly explain why the correlation of the two tasks was increased, so was the confidence in sketch quality, while the correctness across all tasks was not significantly improved.

On the other hand, in comparison with Group *CS*, Group *GS* found it was more challenging to figure out the analog properties of the furniture pieces, with statistically significant differences in size estimation ($p < .01$) and position estimation ($p < .01$), which can be relevant to the fact that Group *CS* consumed significantly more time than Group *GS* exploring the furnished hotel floor plan in the experiment section ($mean_{GS} = 7.13$ min, $mean_{CS} = 11.88$ min, $p < .05$, see Figure 4.11(b)).

Participants from both groups found the sonified functional facilities were easier to locate than the verbally assisted furniture pieces. More specifically, furniture pieces located along the walls were more frequently reproduced correctly, while those piece that are located more distant from the walls were seldom explored and consequently were correctly reproduced by only few participants. This may be a side effect of the classic boundary-following strategy. In particular, when users exploring along the walls, there was neither haptic nor acoustic cue implying the existence of internal furniture pieces. In the interview section, some participants proposed that haptic or acoustic assistance should be invoked in some specific position, e.g. the wall section covered by orthogonal projections of furniture pieces. Some other participants holds the opinion that it should a matter of practice.



(a) Time consumption in the training section

(b) Time consumption in the experiment section

Figure 4.11: Comparison of time consumption in haptic exploration between German sighted participants and Chinese sighted participants. The only statistical significance was that Chinese sighted participants consumed statistically significantly more time than German sighted participants for exploration of furnitured floor plan in the experiment section ($p < .05$).

4.4 Knowledge acquisition in furnished floor plan (Study V Part 2)

4.4.1 Introduction

In the first phase of this study, it has been proved that the modeling task is a reliable testing method to investigate the mental spatial model, and that sighted participants were able to acquired spatial knowledge by exploring haptic-audio virtual floor plans. However, it should never come to the end of a development story of a human-computer interface for visually impaired people without empirical study with real potential users. audio sonifed floor plans. They all explored the same office room plan in the training section, and the same hotel room floor plan in the experiment section as the other two groups of sighted participants in Part 1. The only difference lying in the experimental design was that visually impaired participant were only asked to do the verbal description task and the modeling task after every exploration.

4.4.2 Method

Participants

This study was conducted at Shanghai School for the Blind. Out of the similar concerns as in the focus group study, all the participants were randomly chosen from the students of the most senior grades. For the purpose of better scheduling for the entire study, one pilot study was conducted. The data of nine participants (five female, four male, mean age: 18.4 years, *SD*:1.1 years) were collected and analyzed. Among the eight participants, two were congenitally blind, six had various level of visually impairment with limited light perception. More detailed information of the visually impaired participants is given in Table 4.6.

Table 4.6: Overview of the participants of Study V Part 2.

Nr.	Age (years)	Age of visual impairment onset (years)	Cause of visual impairment	Remaining vision
1	17	congenital	polio	none
2	18	5	glaucoma	none
3	19	congenital	polio	none
4	20	12	retinal detachment	none
5	18	congenital	albinism	dark/light
6	17	congenital	albinism	dark/light
7	18	3	corneal opacities	dark/light
8	19	5	glaucoma	none
9	20	6	cataract	dark/light

One month before the study was conducted, an introduction document was handed to the participants and their legal guardians, to provide the participants with sufficient information of the study procedure and to state the rights of the participants. The introduction document must be signed by at least one legal guardians of the participants before the study was conducted. Class teacher and legal guardians of the participants were allowed to stay in the meeting room during the conducting, but they were only allowed to interact with the participant. Participants who had remaining vision were blindfolded during the exploration, so as to eliminate the visual input of hand movement. Participants did not have an concept of radiator. Therefore, a brief introduction about radiators were given in the introduction section of the study, covering the working principles, color, size, shape, and common location of such facilities.

Stimuli, procedure, and testing methods

Since all the participants were native speakers of Chinese, the verbal assistance were uttered in Chinese. All the other haptic-audio stimuli were exactly the same as that employed in Study V Part 1 (see Section 4.3.3).

Different from Part 1, after each exploration, participants only took the verbal description task and the modeling task. The reproductions done by the participants were photographed and then evaluated by two individual teachers at Shanghai School for the Blind who have not observed any study conduct.

4.4.3 Results

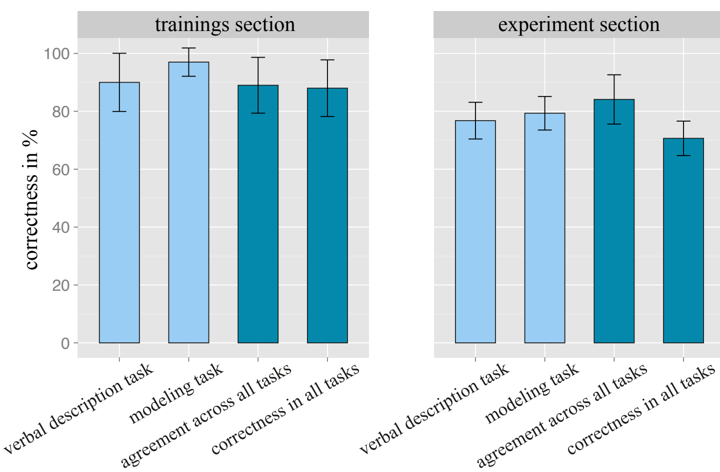


Figure 4.12: Amount of objects reproduced by Chinese visually impaired participants. More objects were reproduced correctly in both verbal description task ($p < .05$) and modeling task ($p < .001$) in the training section than in the experiment section. The cross-task agreement of the training section and the experiment section was not significantly different from each other ($p > .05$).

Performance by visually impaired participants is illustrated by Figure 4.12. In the training section, on average 90% of the objects in the office room plan were correctly reproduced in the verbal description task, and 97% in the modeling task. Mean value of 89% in consistence between the outcome of these two tasks was achieved, and on average 88% of the objects were correctly reproduced in both tasks. In the experiment section, mean accuracy of 76.8% was reached in the verbal description task and 79.3% in the modeling task. On average 84.4% of the outcome was consistent and 70.7% of the objects were correctly reproduced in both tasks. The performance in training section was significantly better than

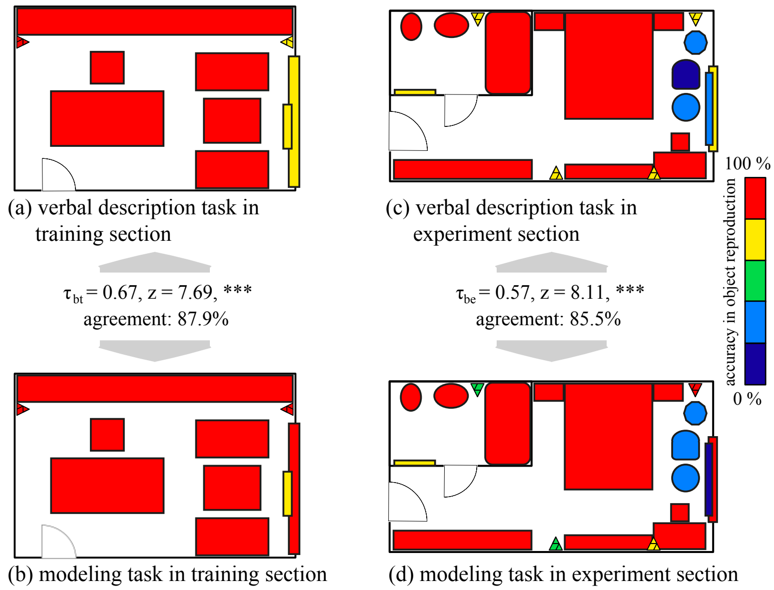


Figure 4.13: Correlation coefficients between performance of two tasks done by Chinese visually impaired participants. The probability of reproduction of furniture pieces was significantly correlated between two tasks in the training section and in the experiment section (*** means $p < .001$).

that in experiment section in both verbal description task ($p < .05$) and modeling task ($p < .001$). Unsurprisingly, difference in correctness of object reproduction across these two tasks was also statistically significant ($p < .01$). The agreement reached between these two tasks in the training section and the experiment section was not significantly different from each other ($p > .05$). The detailed correlation coefficients between the outcome of the two tasks are illustrated by Figure 4.13. The correlation coefficients between the two task were not significantly different from each other. All the facts above showed that visually impaired participants were able to reproduce the mental spatial model acquired from haptic-audio floor plan with satisfying accuracy and that the modeling task was a reliable approach to investigate mental spatial model of visually impaired users.

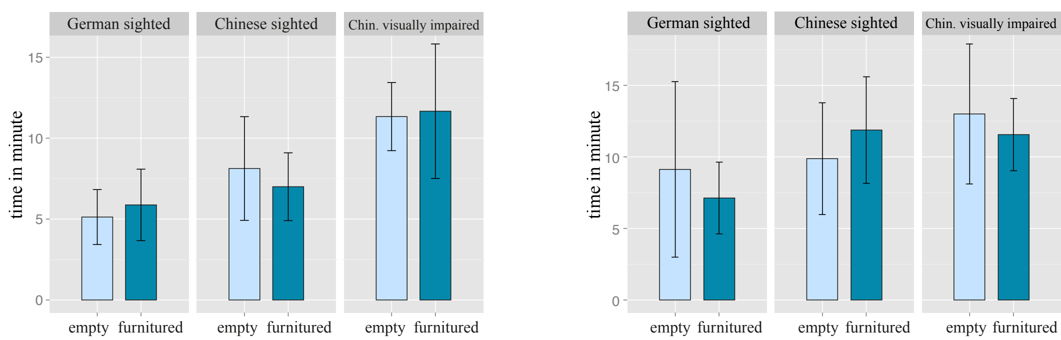
The answers to the questionnaire given by visually impaired participants are summarized in Table 4.7. It was not challenging for the participants to get familiar with the mapping between sonification and representations of the functional facilities (No. 1). They were quite interested in the information about furniture (No. 16). The verbal assistant was considered to be very helpful (No. 6). It was least challenging to figure out the position of the functional facilities. Then it was a little bit more challenging to estimate the size of the furniture pieces. In comparison, it

Table 4.7: Summary of answers to the questionnaire given by Chinese visually impaired participants (1 meat *totally agree*, and 5 meant *totally disagree*).

Nr.	Question / Statement	Answers	Mean	SD
1.	It was challenging for you to get familiar with the mapping between different sound and entities.	4, 5, 3, 3, 4, 3, 5, 4, 4,	3.89	0.67
2.	It was challenging to figure out the shape of the furniture.	3, 2, 3, 3, 4, 3, 3, 3, 3,	3.00	0.50
3.	It was challenging to figure out the horizontal and vertical proportion of the furniture.	4, 3, 3, 2, 4, 2, 1, 3, 3,	2.78	0.97
4.	It was challenging to figure out the size of the furniture.	4, 2, 3, 3, 4, 3, 5, 3, 3,	3.33	0.87
5.	It was challenging to figure out the position of the furniture.	4, 3, 3, 4, 4, 4, 5, 4, 3,	3.78	0.67
6.	The verbal assistant telling the name of furniture was helpful.	1, 1, 2, 1, 1, 1, 1, 2, 1,	1.22	0.44
7.	It was challenging to estimate the position of the windows.	5, 4, 3, 4, 4, 2, 5, 3, 4,	3.78	0.97
8.	It was challenging to estimate the length of the windows.	3, 4, 3, 3, 3, 2, 3, 3, 3,	3.00	0.50
9.	It was challenging it was to estimate the position of the radiators.	3, 3, 3, 4, 2, 3, 3, 3, 4,	3.11	0.60
10.	It was challenging to estimate the length of the radiators.	3, 2, 3, 3, 2, 3, 3, 3, 2,	2.67	0.50
11.	It was challenging to figure out the position of the power-outlets.	5, 5, 3, 4, 4, 3, 5, 3, 4,	4.00	0.87
12.	It was challenging was to figure out the position of the doors.	5, 5, 4, 5, 5, 4, 5, 4, 5,	4.67	0.50
13.	It was important for you, to know about the information of the windows.	3, 2, 3, 2, 1, 2, 1, 2, 2,	2.00	0.71
14.	It was important for you, to know about the information of the radiators.	3, 3, 3, 2, 3, 4, 5, 3, 3,	3.22	0.83
15.	I was important is for you, to know about the information of the power-outlet.	1, 2, 3, 2, 3, 2, 1, 2, 1,	1.89	0.78
16.	It is important to you, to know about the information of the furniture pieces.	1, 3, 2, 1, 1, 3, 1, 1, 1,	1.56	0.88
17.	The experience of using this interface was pleasant.	3, 2, 3, 2, 3, 2, 1, 2, 1,	2.11	0.78
18.	You would recommend this interface to someone else who are blind or visually impaired.	1, 1, 1, 1, 2, 2, 1, 1, 1,	1.22	0.44
19.	The order of empty display and furnished display of the floor plan is organized in a helpful way.	1, 2, 1, 1, 3, 1, 1, 1, 1,	1.38	0.74
20.	You are confident in your performance in the modeling task.	3, 3, 3, 4, 5, 3, 3, 3, 3,	3.33	0.71

was still a little bit more challenging to estimate the shape of the furniture pieces. And the aspect ratio was considered as the most challenging property to figure out (No. 2-5). The information of windows was regarded significantly more important than that of radiators (No. 13, 14, $p < .01$). For both windows and radiators, it was equally challenging to estimate the position and the size in statistics (No. 7-10, $p > .05$). Unsurprisingly, information about power-outlet was important to the participants (Nr. 15). The participants found it not challenging to locate the power-outlets and the doors (No. 11, 12). Positive comment on the two-phase exploration strategy was given by visually impaired participants as well (No. 19). But in comparison with sighted participants, visually impaired participants had stronger wish to be abel to switch back and forth freely between the empty and furnished display of the floor plans. The participants were not very confident in their performance in the modeling task (No. 20). Nevertheless, they thought, it was a pleasant experience to use the interface (No. 17), and they were very likely to recommend this interface to people with visual impairments (No. 18).

4.4.4 Discussion



(a) Time consumption in the training section

(b) Time consumption in the experiment section

Figure 4.14: Time consumption in haptic exploration by Group *GS* and Group *CS* and visually impaired participants.

In this study, visually impaired participants had comparable performance as sighted participants, especially in the experiment section. Some minor difference occurred in the outcome of the training section. Visually impaired participants reproduced more objects of the office floor plan correctly than participants from Group *GS* in the modeling task ($mean_{GS} = .82$, $mean_{VI} = .97$, $p < .01$). Also in the verbal description task, visually impaired participants, reproduced more objects correctly than Group *GS*, however the difference was not statistically significant ($mean_{GS} = .80$, $mean_{VI} = .90$, $p > .05$). This may be explained by the fact that visually impaired participants invested significantly more time than participants from Group *GS* (see Figure 4.14(a)). But no significant difference was found between asks performance of the visually impaired group and Group *CS*, so was in perspective of time consumption. However, the agreement and correlation between outcome of these two tasks were both not significantly different from each other, which supports the validation of the modeling task with visually impaired participants.

One interesting difference was discovered in the reproduction of the sonified radiators. Seven out of the nine visually impaired participants reproduced the radiator in the bath of the hotel floor plan, but only one participant out of the seven reproduced the radiator with the window in the main hotel room. In the interview section, participants reported that they did notice the concurrent sonification for the radiator, but they forgot to tell it or represent it in the tasks. This implies that the participants were able to perceive the sonified spatial overlapping window-radiator constellation during virtual haptic wall-following, however the spatial knowledge of the radiator was not integrated into the mental spatial model of the hotel room. This can also be an effect from the lack of familiarity with radiators by our visually impaired participants (see Section 4.4.2).

According the data of time consumption, visually impaired participants tended to take more time exploring the floor plans than sighted participants. In the training section, on average, visually impaired participants explored the empty office floor plan for 11.1 minutes (*SD*: 6.8 minutes), and 11.7 minutes (*SD*: 4.4 minutes) for the furnished floor plan. In the experiment section, on average 13.0 minutes (*SD*: 3.4 minutes) and 11.6 minutes (*SD*: 4.7 minutes) were consumed in exploring the empty hotel floor plan respectively (see Figure 4.14).

Similar to sighted participants, visually impaired participants produced the furniture pieces along the walls better than those that were not along the walls. And the participants shared strong wish to have access to the pieces that were not perceivable along the walls. Some teachers and students suggested that it may be helpful to introduce primary hand and sub-primary hand protocol in the virtual haptic exploration. Then the primary hand could still exercise the wall-following strategy, while the sub-primary hand may have more freedom to explore the surrounding area of the primary hand, with the primary hand as real-time spatial reference. It was an interesting brain-storming result, but to have more freedom and flexibility in human-computer interaction is similar to a coin with two sides. In order to realize such complex interaction scenario, more complicated hardware configuration would be needed, then the first direct consequence would be that the time and efforts for training phase would increase. Secondly, systematically designed test cases should be thoroughly investigated. And too much simultaneous input from different perceptual channel with rich features in representational multi-modality can arouse more mental work-load for users. Taking such practical concern into consideration, participants shared in this interview section that they would prefer to have an interface with full function which is also easy to get familiar with. As illustrated in the questionnaire, our visually impaired participants thought the nterface was helpful for them to acquire spatial knowledge of novel environment, and they would strongly recommend our interface to other people with visual impairments as a substitution for visual floor plans.

4.5 Summary

The wall-following strategy is the most basic and critical orientation and mobility skill for visually impaired people. This strategy is also efficient and reliable in acquiring spatial knowledge in virtual haptic environment. In real life, it is the contours of every single furniture piece together with the exposed wall section in an indoor environment that define the substantial space within which people can locomote. For sighted people, the real margin of indoor environment can be perceived through vision while movement in real-time. But for visually impaired people, the margins can only be accessible by reaching with limbs or rods, which is low in efficiency. Moreover, furniture pieces whose height is below the arm reach of visually impaired people can be dangerous by trampling them by the feet, or objects fixed high above on the wall can bump the visually impaired people on the head or in the upper body. Therefore, it is necessary to make furniture pieces non-visually accessible to visually impaired users of haptic-audio floor plans.

In this chapter, empirical study with visually impaired participants is reported. Usability of haptic-audio floor plans in providing visually impaired users with spatial knowledge of furnished novel indoor environment is investigated. In the stimuli, both functional facilities and furniture pieces were displayed. Both verbal description task and modeling task were employed since visually impaired participants were not skilled in producing sketches of mental spatial models. The reliability and validation of the modeling task was investigated in advance by two groups of sighted participants, one from Germany, the other from China. And the modeling task was proved to be a reliable testing method for mental spatial models of indoor environment for both German and Chinese participants. The empirical results with visually impaired participants showed that both sighted and visually impaired participants were able to acquire spatial knowledge from the our haptic-audio floor plans, with spatial knowledge of the functional facilities and furniture pieces. In comparison with sighted participants, visually impaired participants consumed significantly more time in exploration of the floor plans, but still in a reasonable and efficient manner. Radiator was a relatively new concept to visually impaired participants at Shanghai School for the Blind, and usually the radiator in the main room of the hotel floor plan was not correctly reproduced.

It can be concluded from this study that it was possible for visually impaired people to get familiar with the interface in short time. The two-phase exploration strategy for the furnished floor plan was regarded as very helpful by both sighted and visually impaired participants. Although visually impaired participants achieved better performance in training section than sighted participants by investing more time in exploring the haptic-audio floor plans, no significant difference was discovered in the performance between sighted and visually impaired participants in the experiment section. Therefore sighted and visually participants are not substantially different as users of the haptic-audio floor plans. And the haptic-audio floor plan can be transferred into a version for users with different linguistic and cultural backgrounds.

Chapter 5

Conclusions and outlooks

5.1 Conclusions

This dissertation, reports on the designing, implementation and testing of a haptic-audio human-computer-interface for spatial knowledge acquisition for visually impaired people. Through exploration in virtual haptic-audio floor plans, visually impaired users can acquire spatial knowledge of the topology and layout, functional facilities, and furniture pieces of the represented indoor environment. The major contributions can be summarize as follows:

1. Haptic-audio representation of topology and layout of indoor environment which supports wall-following strategy and constrains overshoot of haptic exploration under control
2. Investigation upon information of novel indoor environment desired by visually impaired people and referred representation for non-visually accessible objects within bounded regions in virtual environment through a focus group study
3. Implementing haptic-audio representation of analog spatial knowledge involving both linear and 2-D overlap relations and discovering predicator that affect accuracy in size and position reproduction of sonified linear objects
4. Proposal of testing task for spatial knowledge appropriate to visually impaired participants

Plausible knowledge acquisition and update strategy for novel indoor environment with non-visually accessible furniture pieces

In the first empirical study, the difference of internal and external walls of a floor plan were represented with the difference in height of elevation. A virtualization for the door which only produce reasonably small amount of overshoot was reached. So the contour-following strategy was supported in an intuitive way (W. H. Jacobson, 1993; Lahav & Mioduser, 2008), and the occurrence of *lost-in-haptic-space* was effectively avoided (Colwell et al., 1998). The results of usability study showed that users can reproduce the represented apartments with correct topology and satisfying layout. Another find-out was that it was challenging to distinguish non-salient L-shaped rooms from rectangular rooms in by exploration haptic-audio floor plan. In further studies plausibility of representing multiple overlap constellation with representational multi-modality in audio stimuli was investigated. The results showed that users can interpret and reproduce the size and position of sonified functional facilities precisely.

The satisfying results from empirical studies proved the usability of representing linear overlapping constellation with representational multi-modality of audio stimuli in virtual haptic environment. In addition to cases of floor plans, liner overlapping constellation exists extensively in spatial knowledge representation of physical world, based on this conclusion, more scenarios of representing and acquisition of spatial knowledge can be addressed. For example, when visually impaired people would like to learn about the geographical information of a specific area, which is supposed to be New York State in this case, haptic-audio map can contribute to an appropriate solution. As illustrated by Figure 5.1, the boundary of New York consists of a section of Canada-US border, borders between other states, as well as shorelines of North Atlantic Ocean. Some sections of the border line of New York State afford further geographical information. For instance, the Canada-US border section contains terrestrial borders, two maritime borders crossing Lake Erie and Lake Ontario, as well as bank of St. Lawrence River; the border between New York and Vermont starts from the north end with shoreline of Lake Champlain; and the border between New York and New Jersey ends with a section of bank of Hudson River. As a matter of fact, the border of New York also illustrate the preference to employ meridians and parallels in land management. Therefore, it can be meaningful for the haptic-audio map users to acquire the knowledge that the northmost flat section of the boundary of New York stays on parallel 45 ° North, which is, as mentioned before, also a section of Canada-US border. Similar situation takes place with a west-east-oriented maritime border in the middle of Lake Ontario on parallel 43.6 ° North and the west-east border section between New York and Pennsylvania, which stays on parallel 42 ° North (White & United States Bureau of Land Management, 1983). On the other hand, the portions of Lake Erie and Lake Ontario inside New York State can be described as 2-D overlapping in this representation, which can be addressed by 2-D overlapping representation solution proposed in Chapter 4.

With the support of the novel modeling test designed, employed, and validated

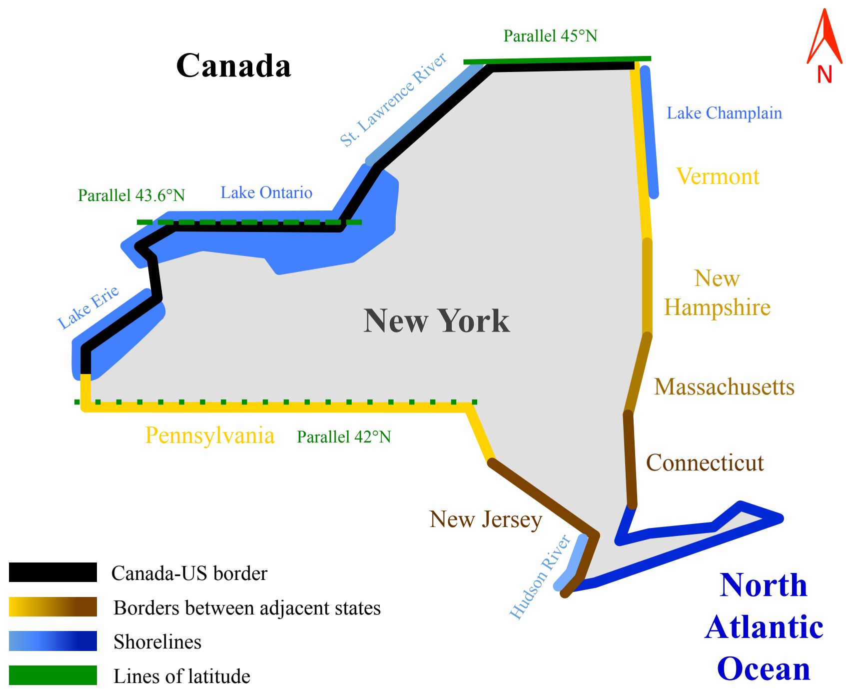


Figure 5.1: Depiction of a proposed geographical map of New York State in haptic-audio virtual environment.

in this dissertation (see details Section 4.3.2 for detailed discussion), reliable data of empirical studies can be collected and analyzed, so as to evaluate usability of such haptic-audio geographic maps. And this testing method can be employed by other implementations dedicating to spatial knowledge acquisition of visually impaired people.

5.2 Open issues

Throughout this dissertation, the *as simple as possible* strategy with respect to the composing of sonifcation was employed. So it has only been taken care of that all the different sonifcation can be distinguished from others. The aesthetics of sonification has not been taken care of in the scope of this dissertation. This issue open to acoustical engineers and scientists, and electronic music technology experts. Some visually impaired participants shared that although the sonification was sufficient for knowledge representation purpose, but was somehow boring. There is not yet a quick solution to improve this situation. Each individual may hold subject opinion of what is pleasant and interesting sonification. It would be a user-friendly feature to let users able to customize what kind of sonification to employed as they wish. On the other hand, it is very important to have a standard inventory of sonification. Some specific sonification should be protocoled to specific meanings. As a benefit, the sonification can gain its employment more generally. Then the training efforts users must invest to get familiar with new sonified human-computer interface can be reduced. For example, the symbol "×" in graphical user interface usually means "to close this window/tab". However, this issue is not likely to be closed without coordinating by authoritative institutions and organizations.

Second, for the purpose of making all the study more under control, there were many constraints. In all the empirical studies, as long as the hapitc interaction point was in contact to predefined area or inside of predefined space, corresponding sonification would fire out. Users could not decide when to only focus on wall-following and when to receive extra information of other functional facilities. Some participants also reported that they felt the sonification could be annoying, when they were trying to for example figure out the shape of the room. And in Study V, all the participants were asked to follow the two-phase exploration strategy. Participants could decide when to display the furniture pieces, but once the furniture pieces were displayed, they were not able to shift back to the empty display of the floor plan. Some participants also had the wish to shift between these two displays more freely. So the second open issue is to grant users more flexibility upon the content displayed during haptic-audio exploration. Although in general the instructed strategy was proved to be efficient, it may also be interesting to observe how users would behave when they can control when to display what.

The third open issue is that the sample of visually impaired participants did not have broad diversity. All the visually impaired participants were recruited from Shanghai School for the Blind, with age between 17 and 19. Therefore, they had the very similar cultural and linguistic background, and could hold many sameness in habits, skills, and behavior patterns. It can be interesting to have feedback from different participants. For example, there are normally no radiators in South China, while they are widely employed in higher latitudes. The question of whether and how life experience of physical window-radiator constellation influents the behavior and performance in dealing with sonified representation is open.

5.3 Future research

Upon the haptic-audio interface reported in this dissertation, some further researches should be considered. The major future research proposed by us is to extend haptic-audio interface with zooming features in terms of both size and contents. For different purposes, users have different requirements for the scope, the level of detail, and the amount of information addressed by a spatial representation. And clues show that the zooming in and out manipulation of spatial representation is critical for the control of spatial attention which involves updating, and processing of mental spatial model (Chen et al., 2009). Therefore, in order to implement this feature appropriately, more systematic research is required. With regard to zooming of contents, for example, when users zoom the *Google Maps*, it is not only the scope of the displayed area, but also the detail level of information displayed also change accordingly. In the global level, only the names and borders of different nations are displayed, while in the street level, even the names of the shops at both sides of the streets are displayed. However, most existing zooming, scaling, and scrolling research only focused on the granularity or the size of objects in the virtual environment (Magnuson & Rassmus-gröhn, 2003; Büring et al., 2008; Rastogi & Pawluk, 2013). The concept of cognitive zooming has been raised (Strohecker, 2000), but has not been employed in display of virtual haptics yet. As a outcome of haptic-audio floor plan with zooming feature, users may explore indoor environment in story-level when it is only necessary to locate a specific apartment, then zoom in to apartment-level to learn about the layout, and zoom in even further to room-level to explore an individual room with furniture pieces displayed.

Besides, if users have to first download and then open a graphic from some other local application so as to review it, it will not be regarded as a user-friendly scenario. Similarly, if a person with visual impairment wants to learn about a novel environment, it would be intuitive and convenient to search for a floor plan of interest and then explore it haptically immediately without leaving the current web page for somewhere else. So the second piece of future work is to implement a web-page application or web browser add-on to support on-line exploration of haptic-audio graphics. With plenty of 3-D model converting tools, it is possible to convert visual graphics to 3-D models that can be explored via virtual haptic devices. This would improve accessibility of non-visual contents in Internet, and maximize the support for both education and entertainment purpose for visually impaired people.

On the other hand, it remains open that to what extend can human, especially visually impaired people, benefit from spatial knowledge acquired from haptic-audio representation in a practical manner. Therefore, it makes sense to investigate whether people behave in a realistic physical novel environment differently when they have spatial knowledge acquired from haptic-audio representation and when they start to explore the physical indoor environment directly. It would also be interesting to see whether there are some differences in the influence of spatial knowledge acquired from haptic-audio representation on behavior between sighted people and visually impaired people.

Appendix A

Evaluation criteria for sketched floor plans

Sketching task, which is one variation of reconstruction-based method to study spatial cognition (Kitchin & Blades, 2002). It is a reliable method for testing human spatial knowledge (Blades, 1990), and it is a easy-to-conduct method, which normally does not require special training or equipments (Lohmann, 2013). However, the evaluation of the sketches produced is a subject work, and it usually dealt with by only one or two reviewers (Billinghurst & Weghorst, 1995; R. D. Jacobson, 1996; Chipofya et al., 2011).

It might be possible for the researchers to keep objective and self-consistent. Nevertheless, being experts in this field, the researchers might hold a set of fixed attitude of what should a good sketch look like. These attitudes can vary from person to person, and they could also be too systematic and scientific and to be appreciated by the multitude. Consequently, these research works might more or less suffer from a hunch that it is subjective. How to make the ratings for sketches more reliable without extravagant human and material resources is a worth thinking question, but has been ignored. In this section, we propose a system of evaluation criteria for sketched floor plans before we employ sketching task in empirical studies.

It is worth of noticing that it is the spatial mental model acquired by users that to be evaluated through the sketching task. Therefore, the spatial properties of indoor environment which are defined in Section 1.3.1 should be the substantial focus in the evaluation process. In order to avoid it case that participants focus mainly on the pure geometric issues (e.g. the straightness of segments, or preciseness of angles), only bare-handed sketches were required. Participants were told not to use any drawing tools such as rules and protractors.

A.1 Proposal of sketch rating criteria for sketched floor plans

A.1.1 Identification of attributes for floor plans

The main characteristics of indoor environments could be described by representations of their geometric features and topological features. Together with the semantic information contained, richer information about the properties of the indoor environment is provided (Whiting, 2006). All these characteristics can affect the perception and cognition of floor plans. Researchers have further identified that the most interesting variables of floor plans are the number of the bedrooms, the shape of the rooms etc. (Ishikawa et al., 2011). In many cases, floor plan has been employed as a representation of indoor environment. Based on the works mentioned above, altogether five variables for simple-structured residential indoor environment floor plans are identified by the authors:

- number of the rooms
- layout of the apartment (the access of the rooms)
- global shape of the entire apartment
- local shape of every single rooms
- position of the doors

A.1.2 Definition of the criteria guidelines

Since there are five variables affecting the results of evaluation on sketched floor plans, and as elaborated and proved by Dawes (1979), linear model is a simple and robust strategy to deal with prediction tasks in such situation. So the computation of the final score is formulated to be (A.1):

$$SCORE = 5(X_{NR} \cdot W_{NR} + X_L \cdot W_L + X_{GS} \cdot W_{GS} + X_{LS} \cdot W_{LS} + X_D \cdot W_D) \quad \text{(A.1)}$$

where the Xs stand for the intermediate results from every rating item, and the Ws stand for the weights for corresponding Xs. Besides, X_{NR}, X_I , X_{GS}, X_{LS} = 0 or 1, X_d = a/n (n is the number of the doors, a is the number of correctly sketched doors) and it holds that:

$$W_{NR} + W_L + W_{GS} + W_{LS} + W_D = 1. \quad \text{(A.2)}$$

Table A.1: Items of sketched floor plan evaluation criteria

Topology	Number of rooms	If and only if the sketch shows exactly the same number of areas as the floor plan, the sketch gets one point.
	Layout	If and only if all the relative positions of the rooms are correct, then this aspect is regarded as correct and 1 point will be earned. If the wall-sharing detail is not correctly revealed, then no point. If the relative scaling of the room sizes are excessively wrong, also no point.
Geometry	Global	If the holes, gaps, or discontinuity within the drawing do not disturb or destroy the geometrical features, then no points will be lost as a result of that.
	Local	1 point will be given when all the areas are correctly sketched with its own local shape.
	Door	The full 1 point is divided into n parts, where n is the number of all the doors appearing in the original floor plan. The point is accumulated with the number the doors, which are correctly sketched. In addition, if a door is too widely sketched to remain clean ranking, the door is not scoring. But in contract, a door will not lose point when it is too narrowly sketched.

Guidelines for evaluation under the supervision of the five rating criteria are documented (see Table A.1). Determination of the weight values and validation of the evaluation criteria for sketched floor plans were abased on empirical studies, which are reported in Section A.2.

A.2 Validation of the criteria

The implementation of this work consists of four procedures:

i. collect raw sketches of floor plans
ii. collect subjective ratings given by good human reviewers
iii. if necessary, adjustment the rating items to resemble the evaluation given by human reviewers
iv. conduct a validation test of the final version of the rating criteria

By good human reviewers, we refer to those who were neither too strict nor too tolerant with the rating, and who were able to stay at a rather stable level of strictness.

A.2.1 Collection of raw sketched floor plans

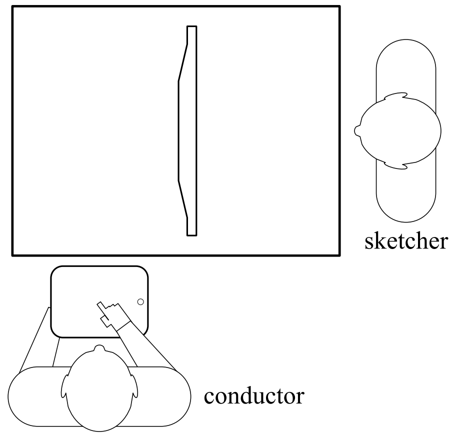
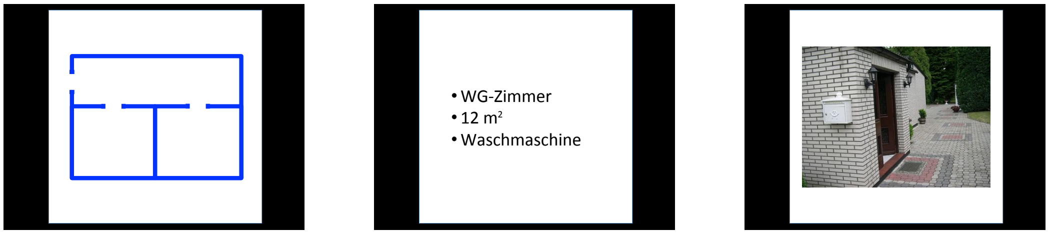


Figure A.1: Setting for sketch collection study

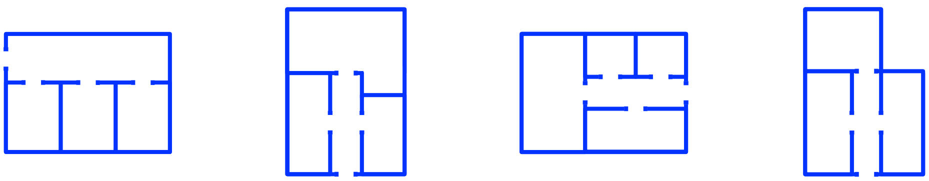
In order to collect a number of raw sketched floor plans, whose quality vary from one another in a natural way, 10 participants were invited as sketch producers (5 female, 5 male, mean age: 22.3 ages, *SD*: 3.6 ages). As illustrated by Figure fig:sketchingConfg, participants as sketchers were faced with a 27-inch monitor, from which visual stimuli was played. The study conductor controlled the display in the monitor via an iPad. Participants were first asked to visually observe a floor plan for 10 to 17 seconds, then some textual information was displayed for 15 seconds, which was in typical format of estate description, after that an image of an apartment was displayed for another 15 seconds (see Figure A.2 for stimuli for the first floor plan in the training section). Then the participants will be asked to first sketch the floor plan displayed at the very beginning, then answer one question about the content of the textual information and one question about the content of the image. All the answers were collected in a booklet, which was printed in A4 size. The sketches were asked to be produced within a box of 16 cm $\times$16 cm large. There were three floor plans in the training section, and another eight different floor plans for the real experiment. After each floor plan, the supplementary textual information, the image, as well as all the questions were different. For example, the questions asked after the first series of stimuli were: (1) How large was the room? and (2) What color did the mail-box have?

Researches show that different people tend to have different focus aspect when dealing with floor plan in the term of cognitions (Ishikawa et al., 2011). Therefore, floor plans employed in the stimuli covered variations in different aspects (see Figure A.3). Floor plan number 1 differs from all the other floor plans in the way that the entrance hall lies on one side of the apartment and goes through the

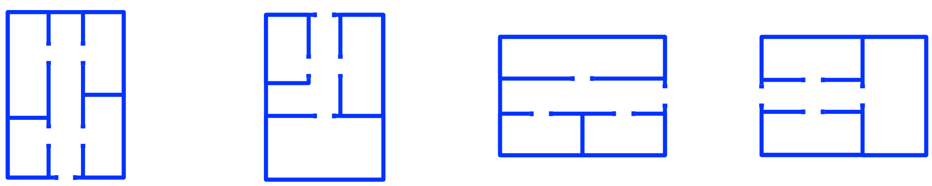


(a) (b) (c)

Figure A.2: Example of visual stimuli for participants in sketch collection study



(a) floor plan No. 1 (b) floor plan No. 2 (c) floor plan No. 3 (d) floor plan No. 4



(e) floor plan No. 5 (f) floor plan No. 6 (g) floor plan No. 7 (h) floor plan No. 8

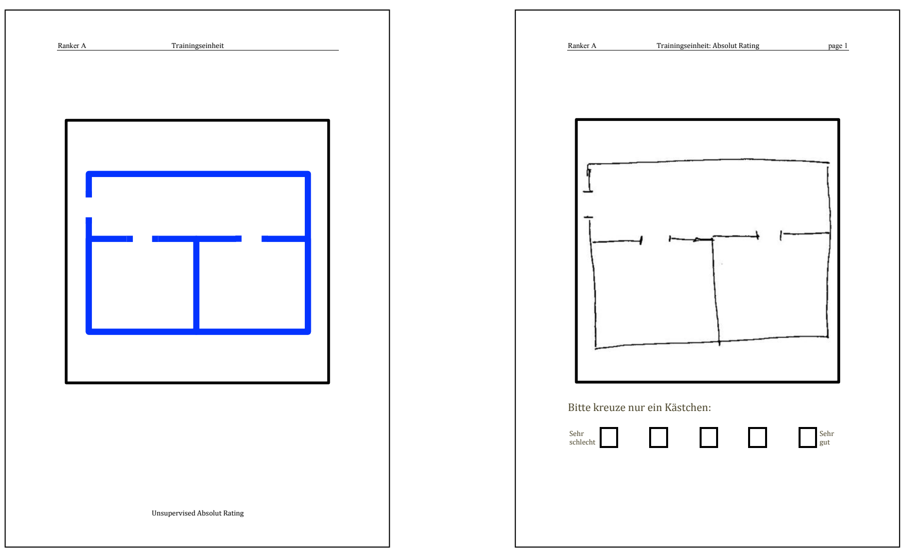
Figure A.3: Floor plan stimuli employed in the experiment section of sketch collection study

entire floor plan and all the three rooms locate on one same side of the entrance hall. Floor plan number 2 differs from all the other floor plans in the way that one room, which is not the entrance hall, is L-shaped. Floor plan number 3 differs from floor plan number 1,2,4,6,7,8 in the way that it has four rooms except for the entrance hall. It differs from floor plan number 5 in the way that all three sides of the floor plan bear access to other rooms while floor plan number 5 only have two walls with access to other rooms. It also differs from 2,4,5,6,8 in that way that the doors of opposite rooms are not directly opposite to each other. Floor plan 4 differs from all the other floor plans in the way that the global shape of the apartment is L-shaped. Floor plan number 5 differs from floor plan number 1,2,4,6,7,8 in the way that there are four rooms except for the entrance hall. It also differs from 1,3,4,7,8 in way that there is only one largest room as well as only one smallest room. Floor plan 5 has two pairs of opposite doors, which is distinct from all the other floor plans. Its entrance hall goes through the entire floor plan in the middle, which is different from 1,2,3,4,5,8. Floor plan number 6 differs from all the other floor plans in the way that the entrance hall is L-shaped. Floor plan number 7 differs from 1,2,3,4,6,8 in the way that its entrance hall goes through the entire floor plan in the middle. Floor plan number 8 has three rooms, which is different from 3 and 5. There is one pair of opposite doors, which is different from 1,3,5,7. The floor plans were displayed to participants in randomized order.

After 80 sketched floor plans were collected. Out of every 10-sketch sample of the same floor plan, two similar sketches were discarded. Finally 64 sketches floor plans were employed as stimuli in the subjective rating collection phase.

A.2.2 Collection of subjective ratings

Altogether 16 participants (8 female, 8 male, mean age: 24.1 years, *SD*: 5.4 years), who did not participate in the sketch collection study are involved in this phase. The goal of this study was to collect data of unsupervised rating on sketched floor plans given by human reviewers.

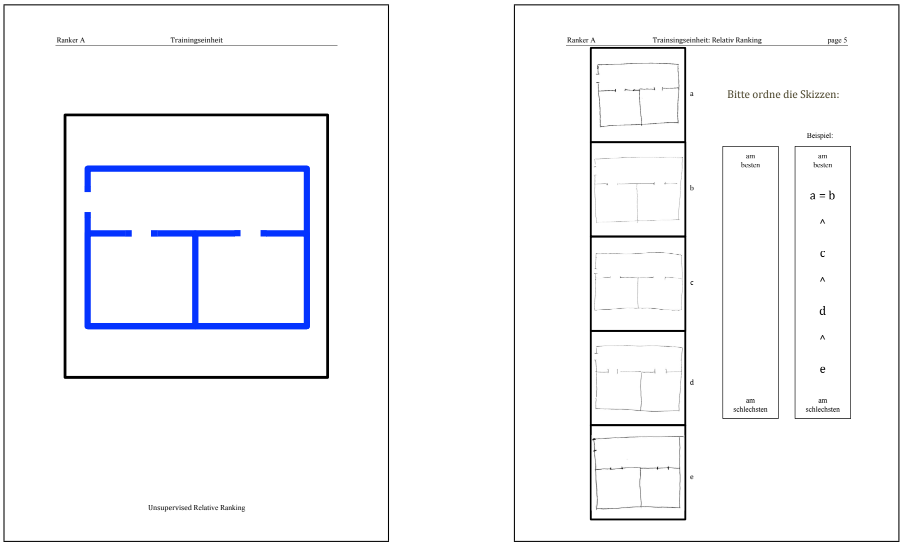


(a) Depiction of the original visual stimulus

(b) Sketched floor plan to be evaluated

Figure A.4: Example of unsupervised absolute rating task of sketched floor plans

Another paper-based study was designed. Each participant received a A4 large booklet, which contained all the tasks to be done. The tasks were divided into two



(a) Depiction of the original visual stimulus

(b) Sketched floor plans to be ranked

Figure A.5: Example of unsupervised relative tanking task of sketched floor plans

separate parts, namely, the absolute rating tasks and the relative ranking tasks. Within the rating tasks, one sketch will be given to one original floor plan. There were five little boxes beneath the sketch. The left-most box was labels as “very poor”, the right most box was label as “very good”. Participants were asked to pick one and only one box from the fives (see Figure A.4). With respect to the raking task, five sketches to one floor plan were displayed in a vertical column, labeled alphabetically from “a” to “e”. Participants were asked to rank the five sketches according to the level of similarity to the original stimulus, with “>”, “<”, or “=” symbol (see Figure A.5). There were 4 absolute rating tasks and 2 relative ranking tasks in the training section, so participants could get familiar with the experimental procedure as well as to establish their individual evaluation principles. In the training section, it was allowed to check and revise the evaluation made earlier. But only when participants claimed that all the absolute rating tasks were finished then they could proceed to the relative ranking tasks. In the experiment section, each participant had 16 absolute rating tasks and 4 relative ranking tasks. It was not allowed to check the former evaluation any more. And the relative ranking tasks can only be started when all the absolute rating tasks were finished.

One important property of the five sketches in the relative ranking tasks was that two of them had been rated by the participant in the former absolute rating tasks. By doing so, the we would like to inspect whether the specific participant held relatively stable judgment for floor plans. The results of the relative ranking tasks showed that two participants usually ranked a lowered rated sketch as better than a higher rated sketch. Therefore, they were regarded as not good reviewers for sketched floor plans, and all the evaluation made by these two participants were discarded from all the evaluation by the human reviewers. So the evaluation given by the rest 14 participants was taken as target outcome given by supervised evaluation made under the rating criteria established in Section A.1. When all the evaluation tasks were finished, participants were asked to asked to report the most important principles they followed when they were evaluating the sketches.

A.2.3 Determinating weights of the rating criteria

Table A.2: Frequency of rating items mentioned in the questionnaire

item	Nr. of rooms	layout	global shape	local shape	doors	total
frequency	8	14	11	11	11	55

Since the raw intermediate results of rating items did not passed the KMO and Bartlett test (KMO-value = .459), principal component analysis was considered as suitable method to determine weights of the five rating variables (Pearson, 1901). The weight determination was done based on the frequency of appearance of rating variable in the questionnaire filled by human reviewers. The five rating variables were the five most frequently followed rating principles by according to the participants. The detailed frequency of occurrence is displayed in Table A.2. So the weight assignment suggested by the questionnaire was:

$$W_{NR} = 0.145; W_L = 0,255; W_{GS} = 0.2; W_{LS} = 0.2; W_D = 0.2 \qquad (A.3)$$

A.2.4 Validation study

The intraclass correlation coefficient between the evaluation given by the human reviewers and the results of the rating criteria was very high (*ICC(3,2)* = .87, p = < .001), which shows good agreement between human reviewers and the rating criteria (Shrout & Fleiss, 1979). More importantly, this agreement was tolerant with variations of floor plans. As illustrated by FigureA.6, for each original floor plan, the evaluation generated by the criteria was always not significantly different from that given by the human reviewers.

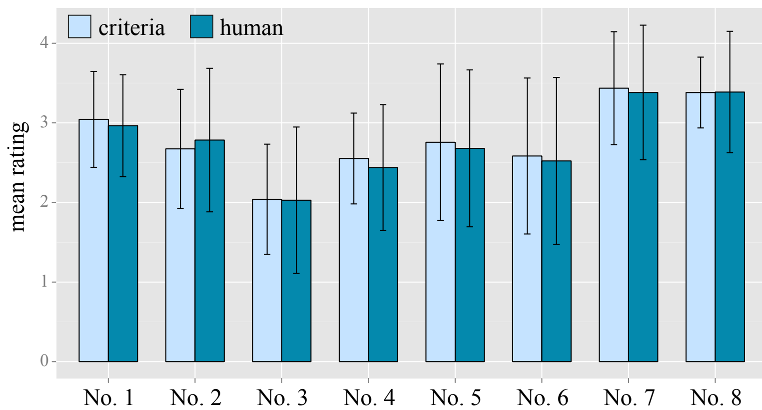


Figure A.6: Floor plan-wise comparison of evaluation determined by criteria and human raters

A.3 Conclusion of rating criteria

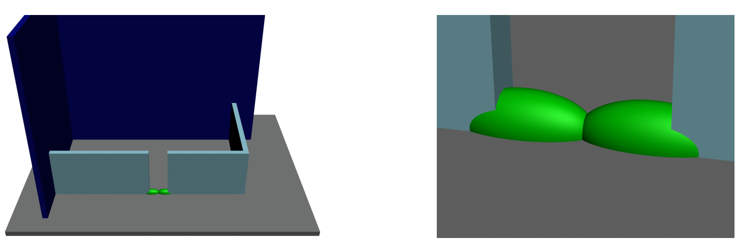
With the reliable rating criteria established above, we were able to evaluate sketched floor plans in a relatively more neutral and objective manner. In the rest part of this dissertation, evaluation on sketched floor plans was all done under the supervision of the criteria. More specifically, although supervised evaluation of sketched floor plans was supposed to be less subjective, individual opinions of reviewers still play a role in the evaluation. Therefore, each sketched floor plan would be rated by two independent reviewers. In case that scores given by two reviewers were different, then the mean value would be taken as final result.

Appendix B

Technical supplimentraies

B.1 Virtualization of doors: solution A

Solution A assigns the curve of two adjacent ellipsoids to the door. Users could perceive the curved during linear wall-following with no efforts. Since there were two eclipses, users could position the haptic interaction point right in the middle of the them. And there was the place lowest height threshold was located. Users can follow the smooth curve in the orthogonal direction to slip through the door (see Figure B.1). With this virtualization for doors in virtual haptic floor plans, users can always correctly locate the doors with no efforts. But an overshoot (see Figure B.2) in after passing through a door occurs frequently, which directly results in *lost-in-haptic-space phenomenon* (Colwell et al., 1998) and damages the continuity of haptic exploration in the floor plans.



(a) (b)

Figure B.1: Solution A for virtualization of the door, which consists of two merged ellipsoids. The grey board represents the floor of the indoor environment; the dark blue blocks represent external walls of the indoor environment; the light blue blocks represent internal walls of the indoor environment.

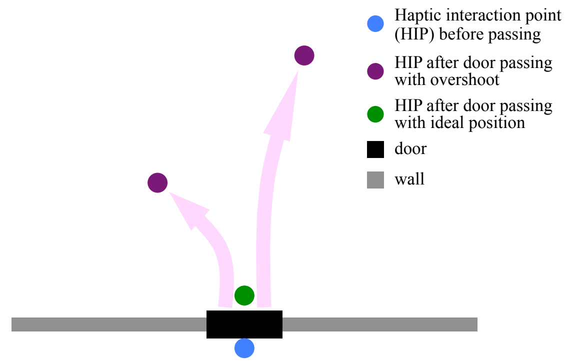
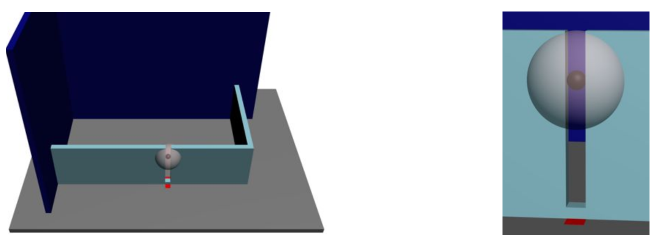


Figure B.2: Illustration of overshoot produced by users after door passing of doors in virtual haptic floor plans.



(a) (b)

Figure B.3: Solution B for designing of the door, which employes magnetic field (which is visually marked up the transparent sphere and haptically unperceivable) to weaken overshoot that occurs in passing-through manipulation.

B.2 Virtualization of doors: solution B

In solution B, the door was represented as a lower ridged opening in the wall with 2 mm in width and 2 mm in height. By either side of the opening, there is a square of 2 mm wide, which had 0.2 for both static and dynamic friction coefficients, so users can detect the doors according to the roughness. Above the opening, there is a ball magnetic feature, which is 15 mm above the floor ground and the could attract haptic interaction point within the range of 10 mm (marked up with transparent sphere in Figure B.3). So when users want to go through a door, they only have to detect and position in the square of higher friction, then lift the haptic interaction point vertically for 5 mm. The magnetic ball would eliminate the overshoot of the haptic interaction point. Finally user could simply drag the haptic interaction point downwards and proceed in the desired direction. With this solution, it was also not challenging to distinguish doors from walls, and the continuity of wall-following was hardly damaged, which was a good balancing situation. However the remaining flaws were that although the amount of training trials is reasonable, the skill to go through thus doors may need a short time of training to master, and that by going through the doors, some overshoot were produced by users. That is to say, after passing through the doors, instead of stationed directly next to the doors, users usually rushed to rather distant area away from the door. But a quick recover of finding spatial reference was possible.

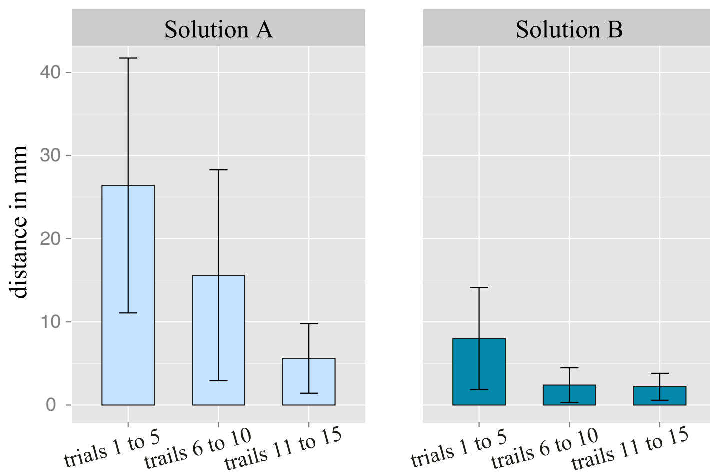


Figure B.4: Comparison of amount of overshoot produced after door passing of two different door solutions. Data samplings from every training phase hold the situation that the amount of overshoot produced with Solution A is significantly greater than that with Solution B ($p < .001$).

B.3 Comparison between Solution A and Solution B for Virtualization of doors

To compare the usability of these two solutions, we conducted a simple usability study with 10 sighted participants (5 female, 5 male, mean age: 25.3 years, *SD*: 3.6 years). We collected the overshoot produced by participants for every five training trails. As illustrated by Figure B.4, in comparison to Solution A, Solution B was supposed to produce significantly smaller amount of overshoot ($p < .001$), and participants can master the skill of going through the door with less training efforts when Solution B was assigned for the representation of the doors in virtual haptic environment. In the usability point of view, solution B for door designing is more user-friendly. However, the pursuit of appropriate door design was proceeding in parallel to the entire dissertation project. Solution A was the most balanced virtualization when Study I and II were scheduled and conducted, and was therefore employed in Study I and II in this dissertation. In subsequent empirical studies, solution B was employed because of the that Solution B arouse significantly smaller amount of overshoot and takes less training efforts.

Appendix C

Mining user expections: a focus group study

C.1 Introduction

In order to make sure that our haptic-audio interface could be helpful to real potential users, it is important to investigate opinions of visually impaired people towards our work (Nielsen, 1993).

Focus group study is appropriate for exploring opinions, feelings, thoughts, and the their reasons of individuals. It is also a very popular form of group discussions for interesting emergent topics which are relevant to the main topic, or seeking for original needs and concerns by the participants (Krueger & Casey, 2000; Liamputtong, 2011). Social scientist introduced its first appearance in the 1920s. In the past decades, focus group methodology has made its wide popularity in many other fields like health, marketing research, and even human computer interaction (Rabiee, 2004; Marshall & Rossman, 2010). The assessment of the haptic-audio interface for visually impaired people fits well in the strength of a focus group study.

The purpose of this focus group study was to present current prototype haptic-sonified floor plans to visually impaired people so as to meet user expectations with further designing and implementation. Therefore, we were particularly interested in what kind of further knowledge was desired by visually impaired people while acquiring spatial knowledge of novel indoor environment via such virtual haptic-audio interface. And how these knowledge should be represented.

C.2 Method

C.2.1 Participants

A lot of preparation jobs, including participant recruitment, room reservation, and transportation of the participants throughout the entire focus group study were dealt by Mr. Jin Hu, director of the office of academic affairs at Shanghai School for the Blind. Altogether 32 participant, 24 students (12 female, 12 male, mean age: 17.17 years, *SD*: .70 years) and 8 teachers (4 female, 4 male, mean age: 37.13 years, *SD*: 9.66 years), took part in the focus group study. 8 students were totally blind (4 female, 4 male, mean age: 16.88 years, *SD*: .83 years), and the other 16 students were visually impaired with limited remaining sight (8 female, 8 male, mean age: 17.31 years, *SD*: .60 years). Four mixed gender groups were scheduled for this focus group study. Each group consists of 2 blind students, 4 visually impaired students and 2 teachers. All the sub-categories of each focus group participants were gender-balanced. It was made sure that among the 6 students, there did not exist any two students who had taken any class in the same classroom ever before, but the two teachers in the same focus group had given classes to all the students. So all the students were familiar with the 2 teachers, but the students are not familiar with each other. Neither the students nor the teachers had experience of focus group study ever before.

We invited the teachers mainly for three reasons. First, there was not enough time to build up friendship between the researcher and the students. But the students had known the teachers for years. And the teachers are those who helped the students most frequently regarding academic study and daily life, when it is taken into consideration that the institute is a boarding school and almost all the students lived at the campus during semester periods. So the students were supposed to talk and behave more naturally when their familiar teachers were present. Second, it was nature to ask questions to the teachers, and the teachers were supposed to be better at encouraging and inspiring the students sharing their individual opinions than those without relevant experience. By doing so, synergy effect was expected to take place during the discussions. Finally, the teachers were also expected to also offer their opinions and feedbacks on our research from the perspective of a teacher. The difficulties and problems they came across during teaching activities are also interesting to us. And we thought it would also be good to take this chance for the teachers to listen to the students need and concern which might not be accessible regularly in classrooms, which may also help the teachers to understand the students from some fresh dimensions.

Consent form was written based on the American Psychological Association's (APA) Ethical Principles of Psychologists and Code of Conduct. It was sent to all participants more than a month before the conducting of the focus group study. In the consent form, a formal request letter for the permission of audio and video recording was also included. And the forms had to be signed by the legal guardians the visually impaired students. At the beginning of each focus group session, the content of the consent form was read aloud again in front of all the participants to acknowledge a personal confirmation. All the 32 participants received uniformed monetary compensation for their time and efforts contributed to this study.

C.2.2 Procedure and stimuli

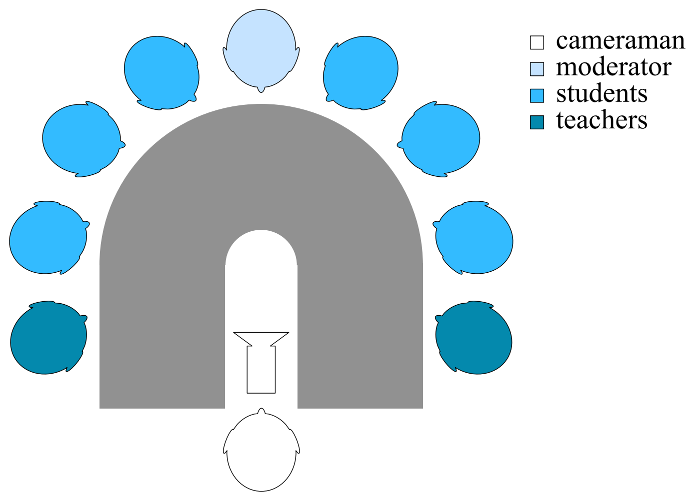


Figure C.1: Setting for focus group study

For each session, all the participants were seated as illustrated by Figure C.1.The moderator sat in the middle of the participants, two teachers sat at the end of the two branches of the table. The students sat in-between. The cameraman was observing the entire discussion, taking the video recordings, monitoring the battery status of the video camera. At the very beginning of each interview session, the general background of the focus group study was given. The second main point was to announce existence of coffee breaks, snacks and beverage in the agenda. The third point was to put the call for a diverse spectrum of opinions to the foreground. We made it clear to the participants that we were interested in their individual feelings, negative feedbacks, identifying of drawbacks, and any relevant emergent themes. By doing so, we would like to establish a friendly and flexible environment for all the participants.

The focus group sessions were conducted using the semi-structured question route (see Table C.1). After each question was raised, all the participants, in-

Table C.1: Question route used to conduct the focus group sessions

Opening questions	
	How did you learn about your apartment?
	How did you learn about the campus?
Introductory questions (role playing questions)	
	If your family is moving into a new apartment, what do you want to know about it?
	If you are going to further your study in a new campus, what do you want to know about it?
	What do you want to know about open areas, such as campus, hospital, etc?
Model exploration session	
coffee break	
Transition questions	
	How do you think about the apartment model?
	How do you think about the map model?
Key questions	
	What kind of difficulties you had when exploring the models?
	What made it challenging for you to understand what was represented?
	How do you think about the windows?
	What else information you would like to learn about from the models you perceived?
	How would you like the furniture or buildings to be re-presented?
	Would you like assisting-tracks for guiding to the furniture or buildings?
Ending questions	
	[All the spontaneous questions occurred during the discussion.]
	Now based on what we have discussed today, can you give some general comments on your attitude and expectations on VE for spatial knowledge acquisition?
	What kind of further practical need can be addressed by VE in your opinion?

cluding the teacher were asked to share their own opinions one after another, in either clockwise or counterclockwise order. We used recording smart pen to take notes and make audio recordings of all the focus group sessions. By doing so, the moderator could be free from heavy work of note taking and get more involved in the discussion. And after the focus groups sessions, more complete and reliable transcripts could be achieved with replay of the recordings.

After discussion of introduction questions, haptic model exploration was scheduled. Due to the transportation limitations of the virtual haptic device, we use physical models instead of the virtual models, and use a chopstick as substitution of the stylus of the virtual haptic device we use in the former research. Exploration of the physical models was designed in *Wizard-of-OZ* manner (Molin, 2004). Categorical knowledge of room types and sonification for analog knowledge of windows were uttered by button clicking of the moderator. In this way, the exploration experience was supposed to resemble exploring the virtual haptic models with virtual haptic device. Since visually impaired students at the institute were adapted to using chopsticks and the verbal assistance was recorded in Mandarin Chinese, there was not supposed to be extra difficulties for the visually impaired students to explore the physical models with chopsticks and meanwhile to understand the information given verbally.

Figure C.3 depicts the 5 physical models employed in the focus group study. There were one apartment model (37×25×5 cm) and four campus models (24× 20× 1.3 cm). The size of the models were controlled, so as to be explored comfortably within the reach range of hands (Koch, 2012). In comparison to the virtual floor plan model, the net height of external walls in this physical model was reduced from 7 cm to 3.5 cm, and internal walls were 0.8 cm tall in stead of 2 cm so as not to block hand movement during floor plan exploration with chopstick. As a matter of fact, This difference lying in the height of the wall did not introduce any difficulty in distinguishing external walls from internal walls for the visually impaired participants. The floor plan model had the same layout as the fourth virtual floor plan employed in earlier empirical study (see Section 2.4 and Section 3.3 for detail discussion). In case the teachers and students had learned about the floor plan from former publications, the window configuration of the stimuli was slightly modified (see Figure C.2).

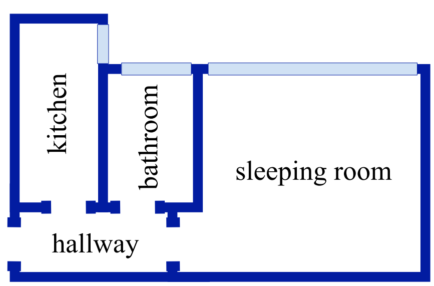


Figure C.2: Depiction of window configuration of floor plan stimuli employed in focus groups study with visually impaired participants

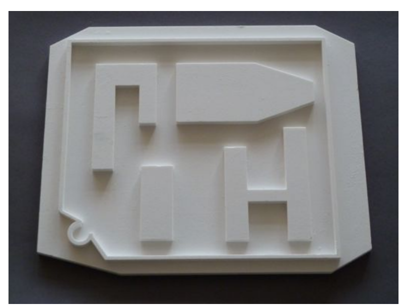
The campus models will have two types of shapes, namely convex and concave shapes. The convex shapes set had a triangle, a rectangle, and a five-sided ploy-

(a) Physical model of floor plan

(b) Indented variant of campus A

(c) Raised variant of campus A

(d) Indented variant of campus B

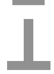


(e) Raised variant of campus B

Figure C.3: Physical haptic models employed in focus groups study with visually impaired participants gon. With the concave shapes we employed those shapes that exist in the symbol convention of both Indo-European and Sino-Tibetan languages (see Table C.2). Two campus layouts were modeled as both elevation and indentation variats. The elevation had a height of 0.5 cm and indentation was always 0.5 cm deep. The models were placed on non-slip pad on the table, so there was no need to keep the models stable with secondary hand. The participants were asked to explore models only via the tip of one chopstick. Contact to the models by the other fingers or the other part of the hand was told to be avoided during the exploration.

Every visually impaired student explored the floor plan and two different campus plans with one having elevation for buildings and the other having indentation areas for buildings. During exploration, participants who still had remaining sight were asked to put on a blind folder. After participants thought they had acquired sufficient knowledge from the models, they were asked to sketch what they had explored on a haptic sketch pad for visually impaired people (see Figure C.4). There was no time limit for model exploration and sketch production. Some examples of the sketches are available in Figure C.5.

Table C.2: Symbols exist in Indo-European languages and Sino-Tibetan languages that are similar to the concave shapes employed in the campus models

Concave shapes in the models	**Similar symbols in Indo-European languages**	**Similar symbols in Sino-Tibetan languages**
	L	ㄱ ㄴ
	X	十 ㄨ
	T	丁
	C U J	凹
	H	工

Video recordings of the focus group study at the School for the Blind in Shanghai were transcribed by two researches. The qualitative analysis of the textual transcript of the interviews were dealt with RQDA (R package for Qualitative Data Analysis).

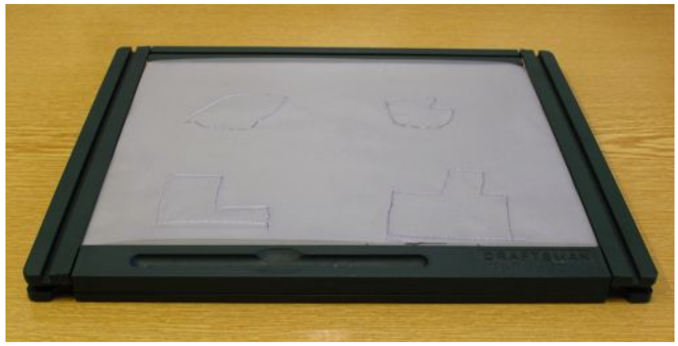


Figure C.4: Draftsman haptic sketch pad used in the focus group study

C.3 Results

First of all, after exploration of haptic-audio models, visually impaired people were able to produce sketches of the environment represented. The quality of the sketches was comparable to that of those produced by sighted participants, which strongly support our hypothesis that visually impaired people were able to acquire spatial knowledge via our haptic-sonified interface.

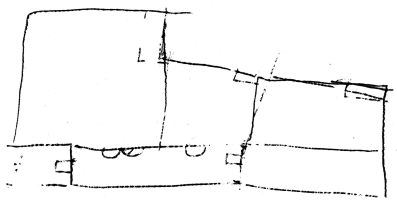
Second, after analysis of the discussion, we came to qualitative conclusions of two main themes:

- When exploring haptic representations of indoor environments, visually impaired people would like to acquire spatial knowledge of power-outlet, furniture pieces, and other fixed facilities.
- In comparison to indentation areas, blocks with elevation was more favored by visually impaired people as representation for objects inside specific bounded region.

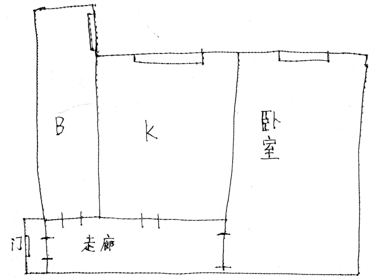
C.3.1 User expectations from the interface

According to what was shared by our participants, although natural lighting function of windows is not really important to them, it was still critical for them to know about the information of windows of indoor environment. The reasons could be summarized as:

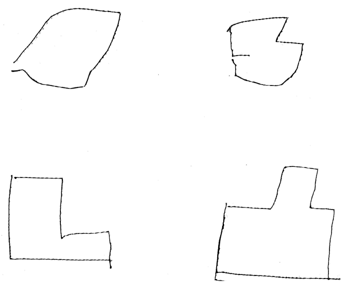
- Visually impaired people were not willing to stay in a totally closed environment. It could bring negative psychological effects like anxiety, being isolated, stressful, etc.



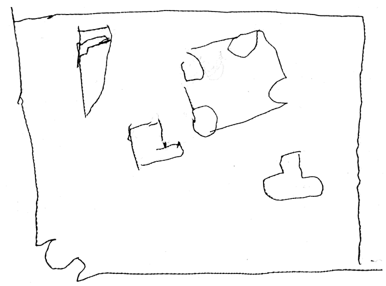
(a) Sketched floor plan by totally blind participant



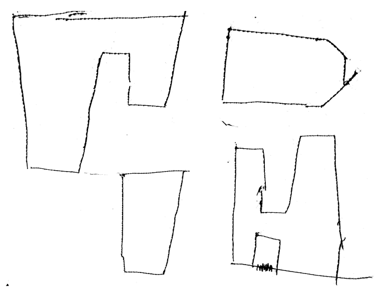
(b) Sketched floor plan by participant with remaining sight



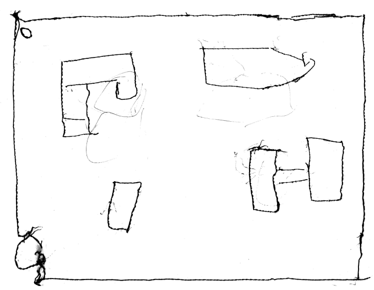
(c) Sketch of campus A after exploration of the indented variant



(d) Sketch of campus A after exploration of the raised variant



(e) Sketch of campus B after exploration of the indented variant



(f) Sketch of campus B after exploration of the raised variant

Figure C.5: Examples of sketches collected during the focus group study

- In addition to the traditional natural lighting and ventilation functions, windows are also very important interface between people inside buildings and the outdoor environment. When a windows is opened, even without the sense of vision, it is possible to detect awful weathers, and other real-time events.
- Visually impaired people perceive and benefit from windows via different modalities as sighted people. Even when windows are closed, sound and noises of traffic or pedestrian still can be heard from inside. Then visually

impaired people would feel more relieved. And when the sun shines, they can still choose a warmer or cooler place to stay as they wish.

After understanding how our haptic-sonfied interface works, the participants all think it was good that the windows and doors were represented in the way we implemented. Beside, they would like to have further access to non-visual representation of power-outlets, furniture pieces, and fixed facilities (see Table C.3). Among the information mentioned above, non-visually accessible power-outlets was most desired. Because they afford the resource of energy for most of the appliances of daily life. But to search for them alone for visually impaired people is usually a frustrating task. Participants shared that they could easily miss such small target when they tried to search them with the pole. It could also be dangerous to touch the power-outlets with bare hands. Besides, they could also be trapped by the cables that are already connected to the power-outlets when they were approaching to them. So when the positions of power-outlets in novel indoor environment is accessible to visually impaired people before they arrive at the physical site, the situation is supposed to be improved.

Table C.3: Summary of entities desired by visually impaired participants from haptic-sonified interface beyond of current prototype

Entitiy of interest	Opinions shared by visually impaired participants
Power-outlets	• They are very small and hard to find. • But they are so important. • It could be dangerous during the search of power outlets.
Furniture pieces	• In fact, the edge of the furniture defines the shape of the rooms. • When we know how the furniture is places then we know the space in which we can move. • They we can know where can we put our staff.
Fixed facilities	• Those are the things that we cannot move freely. • They are very important for daily life.

C.3.2 Elevation or indentation variant for objects in bounded region

Almost all the participants though both elevation and indentation versions for buildings were in general very good. However, more participants though to represent buildings as blocks with elevation was better (see Table C.4). And the difference between totally blind participants and participants with remaining sight was not statistically significant ($\chi^2(1) = 0.8, p > .05$).

With the raised variant, participants had the advantage of recognizing the absolute and relative position of each buildings faster and easier. Whereas the indentation approach provided participants with better support for boundary-following of each building, which made the shape recognition of the buildings faster and easier. With respect to the topic of lost in haptic space phenomenon, participants suffered more from discontinuity during haptic exploration in the raised variant. But many participants considered it as a matter of practice, and were confident in over coming this flaw through a little bit more training. If one had to choose one variant over the other, more participants thought the elevation designing was better for buildings in campus models.

C.3.3 Other emerging general issues

19 out of 24 student participants would be willing to use such interface before they go to physical scenes so as to get general overview of the entire environment. There were mainly two reasons why the other five students were not that interested in the interface we presented. First, they did not believe that the floor plans and maps could always be valid in real time. According to their experience, many updates or dynamic changes are not represented in the haptic floor plans or haptic maps that can be learned in advance. This could arouse extra inconvenience to visually impaired people. Second, they had no confidence in the level of detail of the haptic floor plans and haptic maps. They did not think they had acquired sufficient knowledge of novel environments from our prototype. For instance, expectation for information about power-outlet, furniture pieces, and fixed facilities was not met. Therefore, they still thought it would be the best if someone can keep them company and guide them around in the novel environment during their first visits. On the other hand, they were looking forward to using more comprehensive interface with more desired information non-visually accessible. Some of the students and the teachers believed that multi-point interaction fashion would improve the knowledge acquisition process via such virtual haptic interface.

Besides, we discovered that blind and visually impaired students were not willing to go to novel environment alone. However, they still had the wish to take part

Table C.4: Summary of opinions towards two different representations for buildings in campus model

Criterium	Opinions shared by visually impaired participants	
	Elevation	**Indentation**
Position	• If we want to know the position of the building, then the raised would be better. • With the raised blocks, it was easier to find the borders of buildings • In the going up model, I often slip to other places unintentionally. • I think the up-going one is easier. When I am blocked, then I know I meet something. In the indentation model, I kept wondering why I am still not falling down.	• When I fall down, I know immediately that here is something. • In the indentation model, it is difficult to switch between the buildings. • Sometimes I felt down unexpectedly, sometimes it takes longer time to find a specific indentation.
Shape	• At the beginning, I though the object on the top-left of the campus is a rather simple shape. But later on I figured out it was more complicated. • For pariticipants having remaining sight, raised variation can offer a better view of the whole campus.	• I think it the focus is on the shape then the indentation style is better. • With complicated shapes the indentation could be better. • Personally I think the indentation is better. Especially with some complicated shapes. I can tell the shapes faster. • I like the indentation as well. The raised one is more difficult to tell complicated objects.
The "Lost in haptic space" phenomenon	• I did not lost contact to the objects. I only have to slow down, and then it is no problem. • I think if the objects were made going upwards, it would be clear to us after several trials.	• I did have to worry about slipping away from the objects.
Summary	Six totally blind participants and nine participants with remaining sight preferred the raised variant.	Two totally blind participants and seven participants with remaining sight preferred the raised variant.

in some feasible tasks, or decision making occasions in an independent manner, which was in line with what reported by other researchers (Khadka et al., 2012).

Finally, according to our participants, traveling and mobility was the activity which they struggle the most, especially traveling with buses and dealing with stair cases. We learned that for visually impaired people in Shanghai, to travel with subway system was regarded as better than other public transportation methods due to existence of escalators, real-time announcements, unoccupied blind roads, predictable stationary position of the trains, etc.

C.4 Discussion

In this study, we presented out haptic-audio interface to real potential users and collected feedbacks in the form of a focus group study. Visually impaired participants thought our prototype was easy to understand and were able to get familiar with the operation in short time. An average, it took three to eight minutes for the participants to explore a floor plan model or a campus model. Through the exploration, spatial knowledge of the represented environment could be learned and then reproduced in the form of a sketch. Although quality of the sketches was severely influenced by limited sketch ability of visually impaired participants, correct layout of the environments could still be clearly recognized. During the exploration session of the focus group study, participants were able to recover from discontinuity and lost in haptic space by themselves. And they were confident that better manipulation of such interface could be achieved with reasonable amount of further training. Taking these facts into consideration, visually impaired participants in Shanghai basically had similar opinions and performance in reproduction as the sighted participants in Hamburg. So it implied that it is reliable and sensible to conduct further usability studies with sighted people before real empirical study with visually impaired participants.

With respect to the proposal of a system with multiple haptic-interaction-point rendering haptic force feed-back concurrently, it would be certainly feasible in the technology perspective. However, a user-friendly non-visual knowledge representation algorithm communicating spatial knowledge involving more than one haptic-interaction-point is still missing. It could exhaust the variations of both perceptual multi-modality and representational multi-modality in human-computer interaction. And the risk that the training period for using such multiple haptic-interaction-point would increase dramatically. But we have to confess that if all the interaction and usability problems were solved, visually impaired people are supposed to benefit from interfaces with multiple virtual interaction proxies. For example, devices as CyberGrasp[1] would make it possible for users to explore virtual objects with more fingers or with two hands (Shahabi et al., 2001; Zhou et al., 2005). Therefore, in spite of the price (roughly half a million Euros for one CyberGrasp, including software) we think it makes sense to start a prototype of virtual haptic interface with two interaction point and test it extensively under non-visual scenario test cases. But this piece of work is not covered in this dissertation.

In addition, through the conducting of the focus group study we found out that it was feasible for visually impaired participants to do sketching tasks, but it was not considered as optimal by us. Sketch producing is a skill which was

[1] http://www.cyberglovesystems.com/products/cybergrasp/overview

not familiar to visually impaired participants. They usually found it challenging to express accurately what they really had in mind. As a consequent, sometimes visually impaired participants had to make verbal description of the sketches they produced so as to clarify their real intention. Second, during the sketch production with the haptic sketch pad, fingers and hands of the participants could easily get stained by the ink or lead of writing instruments. Therefore, a more appropriate testing method for visually impaired participants should be designed.

Finally, for the purpose of meeting expectations of potential users, power-outlets would be represented by sonificaiton in haptic-auduio floor plans. And furniture pieces would be implemented non-visually accessible as blocks with elevation. Before we conduct further empirical study with visually impaired participants, newly implemented interface would be tested with sighted participants in the first place.

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