A Haptic-Audio Interface for Acquiring Spatial Knowledge about Apartments

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Abstract. In selecting an apartment for residence, floor plans are a common source of relevant information. For visually impaired people, adequate floor plans are widely missing. This paper introduces a haptic-audio assistance system, which is designed and implemented to help visually impaired people to acquire the layout of novel small-scale apartments. Virtual 2.5-D floor plan models are made according to—traditional visual—floor plans. Haptic force feedback will be rendered when users explore the virtual model by a PHANToM Omni device. During the exploration, auditory assistance information about floor plans, either by speech or by sonification, is invoked by entering into prescribed areas, which are placed on the inner contour of rooms. Two user studies are presented which demonstrate the usability of the haptic-audio interface. In particular, reinforcement and extra positive influence brought by the employment of multiple modes in audio perception channel is confirmed.

Keywords: Spatial Knowledge Acquisition, Virtual Haptics, Haptic-Audio Floor plan, Sonification.

1 Introduction

The use of spatial knowledge is ubiquitous in our daily life. For example, the task of selecting a residence to rent is not possible to be accomplished without spatial knowledge of the apartment. Floor plans, which inform people about the apartment's overall layout as well as of the individual rooms and the relationships between them, are commonly used external representations of indoor environments. For visually impaired people, the information presented by traditional floor plans is not directly accessible. In order to overcome these limits, appropriate substitution is required.

Tactile maps are effective means for blind and visually impaired people to acquire knowledge of their urban environment. As Espinosa and colleagues [2] point out, tactile maps can potentially increase the autonomy of blind and visually impaired people. Whereas visual perception supports comprehension processes, which switch between global and local aspects of a graphical representation, haptic perception has a more local and in particular a more sequential character. Thus, compared to visual maps, one drawback of tactile maps is the restriction of the haptic sense regarding the possibility of simultaneous perception of information (for an overview see [8]). In the

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case of haptic map-reading, the sequential character of haptic exploration demands additional effort in integrating of information over time. As a consequence, this leads to limitations in building up cognitive maps, such as more sparse density of information and less sufficient survey knowledge.

The increasing availability of haptic interfaces for human-computer interaction (HCI) offers a large variety of prospects for training and assisting blind people. In particular, by the means of such devices (for example, the PHANToM® Omni) it is possible to realize map-like representations of physical environments that are HCI-counterparts to traditional tactile maps. To overcome the '*integrating spatial information over time*' problems of haptic exploration, providing additional information, such as auditory assistance through the auditory channel, has been proven to be helpful [7]. Several multimodal systems have been developed that use sounds or prerecorded speech when objects on tactile maps are touched (e.g., [9], [18], [20]) or that generate sentences aware of the current act of exploration [6], [7]).

In contrast to maps, floor plans, which are a kindred type of graphical representations, play up to now a minor role in the development of haptic—or even audio-haptic—interfaces (but, see e.g., [15], [13], [5]). Whereas most maps of urban environments have 'paths' as primary graphical entities and thus line-following constitutes the main haptic exploration strategy [3], floor plans possess regions, depicting rooms or hallways, as primary graphical entities and border-following as main haptic exploration strategy. This contrast between maps and floor plans, which is based on the graphical inventory and the consequential exploration procedures, restricts the portability from haptic-audio maps to haptic-audio floor plans.

In this paper, we introduce a haptic-audio interface addressing floor plan based spatial-knowledge acquisition of apartments to be usable by blind and visually impaired people (see Fig. 1). The remainder of the paper is organized as follows: In Section 2 we describe the main objectives of the proposed system and the 'division of labor' among the haptic and the auditory (sub-)modalities. In Section 3 we present results of two experiments—performed with blindfolded participants—concerning the shape comprehension and the processing of information about windows. We decided to test the system with blindfolded sighted participants rather than with blind or visually impaired participants because of two reasons. Firstly, blind and visually impaired people are not always familiar with floor plans. Thus effects of becoming accustomed to floor plans can be excluded with blindfolded sighted participants. Secondly, one goal of the studies reported here was to develop, refine and evaluate different principles of multimodal floor-plan exploration before testing the system with visually impaired people (cf. [7] regarding map-exploration assistance). Follow-up experiments with blind and visually impaired people are planed.

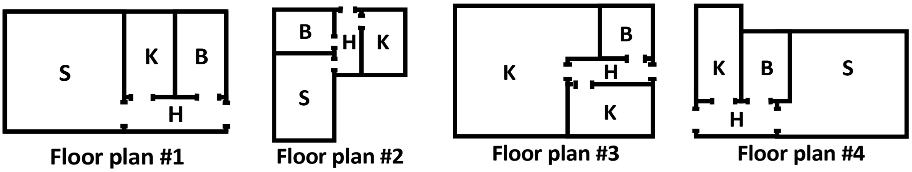


Fig. 1. Virtual floor plans employed in Experiment 1

2 Towards Haptic-Audio Modeling of Simple Floor Plans

Using floor plans to get an initial impression of an apartment provide various spatial properties of the rooms and their spatial configuration, such as size and shape of rooms, the position of doors or the location of windows. To sum up, a tactile floor plan should—similar to tactile maps—provide a blind or visually impaired person with the possibility to build up a mental representation of the apartment in question by haptic exploration of a virtual model. Beyond acquiring knowledge about the individual rooms, a 'picture' of the apartment as a whole should also be possible to be constructed. Last but not least, for living in an apartment, functional aspects of rooms are highly important, e.g. 'being a bathroom / the hallway', 'having a window', etc.). Appropriate information can be provided by the haptic-audio interface.

Various studies on tactile-map use and similar applications—see, for example, [9], [12], [15]—give evidence, that maps and floor plans for blind readers should be limited in detail and complexity. To constrain the variations of our empirical studies, we chose the following constraints on floor plans and thus on the depicted apartments to be explored by blindfolded people. For the experiment 1 (see Section 3.1) the constraints are as follows (see Fig. 1): (1) number of rooms: hallway and three function-rooms, bath, kitchen and sleeping room; (2) shape of rooms: rectangular vs. L-shapes; (3) size and proportion of rooms: sizes of rooms as well the proportion of side-lengths are limited to a small number of values; (4) accessibility: all function-rooms have a door to/from the hallway, there are no doors between function rooms (This—so-called—palm-structure avoids loops in exploring); (5) global shape:, i.e., shape of the apartment: rectangular vs. L-shapes.

2.1 Haptic (re-)presentations

In accordance to other approaches for (re-)presenting maps, floor plans or room plans to be explored haptically ([5], [9], [15]), we use virtual 2.5-D plans—realized with the open source library Chai3D—explored via a Sensable PHANToM Omni force feedback device. In our virtual haptic floor plans, only two elementary entities are represented by force feedback. Solid borders are used for 'walls' of the apartment, and two end-to-end emerged ovals stand for 'doors' (see the training floor plan in Fig. 2).

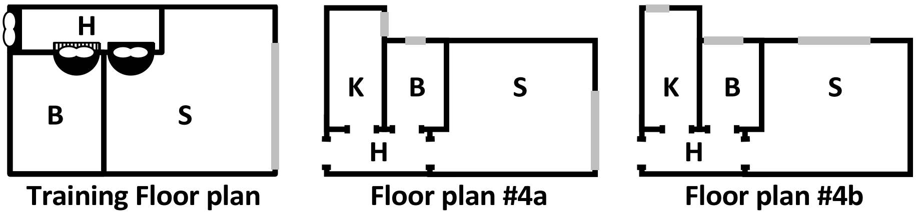


Fig. 2. Virtual floor plans (with windows: gray shaded) used in Experiment 2

When the haptic interaction point touches different components of the virtual floor plan, either stable linear force feedback or wavy force feedback is rendered accordingly. There are two types of ‘walls’, namely external walls, which define the global shape of the entire apartment, and internal walls, which form the boundaries of different functional areas, i.e. rooms. The external walls are 7 cm in height, and the internal walls are 2 cm, i.e. both types restrict leaving the room. Although there is no ‘roof’ on the top of the apartment constraining the exploration of the user, jumping over the walls to go from one area to another by lifting the stylus up has not be applied by the users. The two-oval design for the door enables the user to distinguish the door from ‘open space’ by perceiving wavy haptic stimuli from the stylus. The wavy stimuli are mild and smooth, so the users can detect the existence of the door, but they are still conscious of travelling in a linear track. The groove in the middle of the door helps the users to anchor themselves, and makes it easier to go through the doors.

2.2 From ‘Haptic’ to ‘Haptic-Audio’: The *Division of Labor* Advantage

As Sjöström et al. [15] in their pioneer prototype of virtual indoor environment describe, their users had high success in learning the correct number of rooms of an apartment, and even in an office-building scenario (with 18 rooms) a majority of their users were able to identify one specific room. This confirms that number-of-rooms problems are in the scope of haptic floor plan use. Additionally, explorations with respect to shape, size and proportion of rooms correspond to haptic capacities, are well investigated in haptic-perception research in general, namely perception of shape, length and orientation [16]. Researches on haptic-interfaces, and even specific investigations on tactile graphs, maps and floor plans for blind users correspond to these findings [12].

As mentioned above, knowledge about the function of individual rooms is essential for the user, and in addition, knowing the functional property of rooms decreases the effort and memory load for discrimination, i.e. for identifying, the rooms. In revisiting a room as well as for remembering the properties of a room after exploration, conceptual labels, as “bath room” have an advantage over complex spatial determiners as “the second room at the left side of the hallway” (Both specifications in quotes stand for internal representations of the user, not for natural language expressions.) To give the user this information, speech, i.e. the auditory modality, is more appropriate as the haptic modality (Braille).

A second field for haptic-audio multimodality we want to discuss in the following is the ‘spatial overlap’ of entities. Windows, which can be conceptualized as openings in walls, are visualized in standard floor plans mostly by shadowing, color-coding, etc. These conventions are not easy to transfer to tactile maps. In contrast to doors, whose tactile-map counterparts should be traversable in haptic explorations, windows should not be permeable. Due to the ‘spatial-overlap view’ on windows, namely that windows are parts of walls, haptic following of a wall is—for some parts of the wall—also the following of a window. Therefore, a separation of these exploration events is suitable: wall following is done haptically, window following is perceived by audition. In other words, the tasks are distributed to the haptic modality and the auditory modality based on principles of ‘division of labor’. Furthermore, within the auditory modality, namely between speech and non-speech audio of different types

[11], also 'division of labor' principles should be in use. In our interface all the invoking areas for audio assistance cannot be felt by exploring the virtual haptic floor plan.

2.3 Audio Assistance: The Use of Speech and Sonification

Beyond standard visual-graphical interfaces, in particular auditory interfaces, using speech and sonification as two representational sub-modes for audio assistance, are successfully employed in multimodal human-computer interaction ([10], [11], [14]).

The floor plans used in Experiment 1 (see Section 3.1) use verbal labels, presented by speech, identifying rooms by their function. The audio assistance over room types is triggered by visiting an 'invoking area' (depicted by shaded half-circles and rectangles in Fig. 2: training floor plan). When the user goes back to the hallway from any other rooms, the system tells, "You are back in the hallway." Since all virtual apartments are rendered from realistic palm-structured residence apartment, the confirmation information of a second visit will only be given in the hallway.

The sonifications used in Experiment 2 (see Section 3.2) are designed to be continuous harmonic beeps, which start when the window areas are touched by the haptic interaction point. When there is only one window, the beep is pitched at 250 Hz.. In case of two windows in the same room, one will stay with 250 Hz, the other one will have 1000 Hz. So in the first place, the participants are supposed to be aware of the existence of the window(s) within possibly the shortest time and least mental effort. Then the users may integrate the speed of the their exploration with the duration of the beeps into an estimation of the length or proportion.

3 Experiments

Two user experiments are reported in this section. With Experiment 1, we tested a haptic-audio interface as a substitution of tactile floor plans. In Experiment 2, sonification for windows was employed as reinforcement of Experiment 1. Not only the results of the individual experiments but also the comparison of the results is reported.

3.1 Experiment 1

We conducted a repeated-measures experiment with four different virtual floor plans. Before the real experiment, all 20 participants (11 female, 9 male, mean age: 23.8 years, *SD*: 2.28 years, they were all university students having little or no experience with haptic force feedback devices) were trained how to operate the force-feedback device and how to deal with the experimental tasks. In the experiment, blindfolded participants had no time limit to explore each virtual floor plan till they claimed that they had learned the floor plan well enough. Then the participants were asked to produce a sketch of the floor plan in a 12 cm by 12 cm sized box printed on the answer sheet, and then to do a size-ordering task, which was to formulate a chain of inequations to present the relative size of all the four different rooms of the apartment. For example, "sleeping room > kitchen > bathroom = hallway" means: The sleeping room was the largest. The kitchen was the second largest. The bathroom had the same size as the hallway and they are the smallest.

Since variations in floor plan features have different influence on human recognition [4], in order to discard the order effect of the experimental conditions (four different virtual floor plans), the Latin Square Design (see [1]) was used.

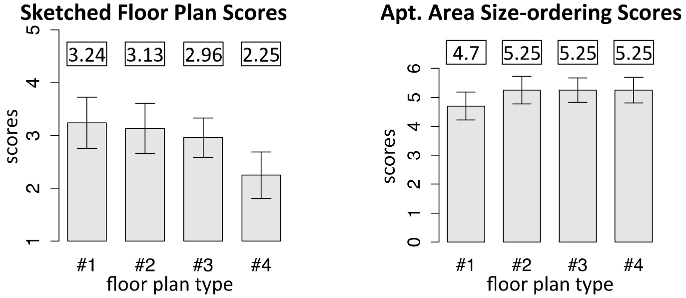


Fig. 3. Evaluation results of the sketch task and the size-ordering task (In this paper, all bar charts are modified with the mean values and the 95% confidence interval of them.)

The scores (range from 1 to 5) of the sketched floor plans are computed as a weighted sum considering five—separately scored—aspects: (*NR*) number of rooms, (*LA*) global layout/topology of the apartment, (*GS*) global shape of the apartment, (*LS*) local shape of the rooms and (*PD*) position of doors. The score function (aspects and weights) is based on an empirical study, in which 16 raters graded 64 sketched floor plans (see [19]). In this virtual floor plan experiment, the results show that the scoring of the sketches was significantly affected by the specific floor plan explored, $F(3,76) = 5.57$, $p < .05$, as the sketches of #1 are highest rated, then #2 and #3, and #4 the lowest. Post hoc tests using Bonferroni correction revealed that the performance of #1 was significantly better than that of #4, $p < .05$. This implies that L-shapedness had influence on sketching producing after the exploration virtual floor plan. The weakness revealed in the sketches of #3 and #4 was mainly resulted from taking the L-shaped sleeping rooms as rectangle.

To analyze the performance of the size-ordering task, the chain of inequations representing the size-ordering of the four rooms of the apartment was first decomposed into six binary inequations. The derived six binary inequations corresponding to the former chain of inequations example would be: “sleeping room > kitchen”, “sleeping room > bathroom”, “sleeping room > hallway”, “kitchen > bathroom”, “kitchen > hallway”, and “bathroom = hallway”. Answering each binary inequation correctly 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, $F(3.76) = 1.51$, $p > .05$. The most common mistake was to regard a kitchen as bigger than the bathroom. Noticing the fact that in most residences the kitchen has larger area than the bathroom, we assume that participants’ own experience has influence on the size-ordering task. The lower mean performance when floor plan #1 was explored could result from the fact that the kitchen, the bathroom and the hallway had very similar size, and further more the bathroom and the kitchen were equally sized, which lead to a comparably larger number of errors in the inequation chain.

With this experiment, we claim the possibility of acquiring relevant knowledge about small-scaled apartments, including the number of the rooms, the name of the rooms, the access of the rooms and the geometrical features of the rooms as well as that of the apartment as a whole

3.2 Experiment 2

Based on Experiment 1, the virtual floor plans of Experiment 2 were augmented by sonifying windows. For every original floor plan two different window configurations, named by "a" and "b", were implemented. There were two or three windows in each apartment, with at the most two windows in one room. The value of 'window-length to wall-length' ratio varied between 0.25 and 1 (seven ratios). The windows were always embedded in external walls of the apartment, as exemplified in Fig. 2. For experimental condition assignment, the virtual floor plans in a specific Latin Square were either all with window configuration "a", or with window configuration "b" (Table 1). The total number of virtual floor plans with each window configuration was counterbalanced. After each exploration, the participants went through the same tasks as in Experiment1, and in addition, they gave their opinion on the importance of information about windows in a questionnaire at end of the experiment.

Table 1. Experimental Condition assignment of the Experiment 2

Subjects	Experimental Configurations			
Sub 1	#1a	#4a	#2a	#3a
Sub 2	#2a	#1a	#3a	#4a
Sub 3	#3a	#2a	#4a	#1a
Sub 4	#4a	#3a	#1a	#2a

According to the outcomes so far, all 8 participants (3 female, 5 male, mean age: 23.4 years, *SD*: 2.7 years, they were all university students having little or no experience with haptic force feedback devices, and had not participated in Experiment 1) succeeded in telling the correct number of windows in any room, as well as the total number of windows in the apartment, and they located the windows to the walls correctly. When the value of the window-wall proportion in the virtual floor plan increases, the reproduced proportion in the sketches climbs up. The windows to wall proportion is not very precisely reproduced. In answering the questionnaire, participants usually claimed that the existence and the number of the windows were important to them whereas the exact position and the size of the windows were not. In spite of the report, the sketched window-wall ratio was significantly related to the ratio in the original models, $\tau = .40$, $p < .001$ (Kendall's tau). One assumption could be that the participants were not motivated to figure out the precise window-wall ratio in the apartment exploration scenario. This experiment is scheduled to include 24 empirical trials. Since the conducting is currently not completed, only the preliminary results of the first 8 participants are reported in this paper.

3.3 Comparison of the Experiments

Using the extended interface providing supplementary information about the windows by sonification, some participants achieve better performance in floor plan sketching (Fig. 4). The average of sketch production scores increased from 2.91 to 3.55, $t(110)= 2.99$, $p < .01$. This improvement mainly results from better recognition of L-shapes in local and global forms. The percentage of participants who recognized the L-shape in floor plan #3 and #4 increased from 45 to 87.5, and from 25 to 37.5. With respect to the recognition of the global L-shapedness, all of the eight participants who explored with sonification can tell the global L-shape of apartment #2, whereas 75 percent succeeded in recognizing the L-shapedness of #4, which is improved from 50 percent. Furthermore, when the 'windows' are placed on the concave edges of the global L-shape, it seems to be very evident clues over the global shape for the participants. All participants who explored floor plan #4a were able to tell the global L-shape, but only 50 percent with #4b. The scores of the size-ordering task in the Experiment 1 (*Mean* = 5.11, *SE* = 0.13) did not differ significantly from those of Experiment 2 (*Mean* = 5.53, *SE* = 0.13), $t(110)= 1.86$, $p > .05$.

With this result, we claim that the employment of sonification provides the users with richer information without obvious negative side effects detected.

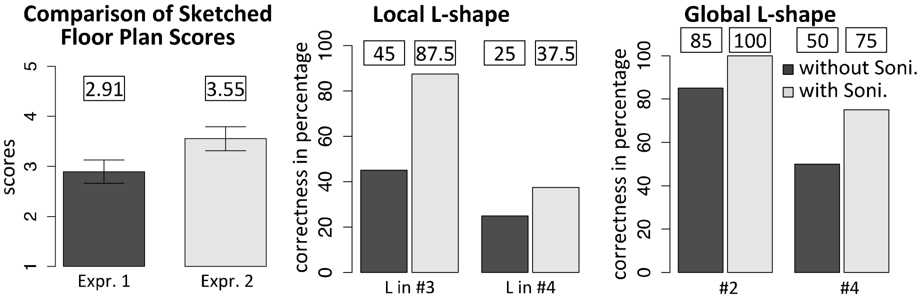
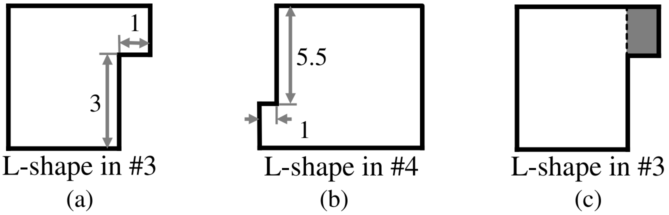


Fig. 4. Comparison between interfaces without sonification and with sonification

4 Discussion and Future Work

Both experiments show that comprehensive knowledge of small-scale apartments could be acquired using the haptic-audio interface. When the interface was augmented with sonification, users were able to acquire supplementary information about windows and show additional improvement in two evaluation tasks. In order to attain more complete and convincing results, additional trials of Experiment 2 are currently ongoing.

Although the recognition of L-shapedness has been improved in the second experiment, systematic analyses of L-shape-phenomena are pending. The proportion of the two edges of the concave corners seems to be one parameter affecting users' perception and cognition. The concave-edge-proportion (CEP) of the L-shaped room in floor plan #3 is 3, while that of the one in floor plan #4 is 5.5. An assumption of the authors is that the closer the value of CEP to 1 is, the easier it is for the users to recognize the inside corner (Fig.5 (a) & (b)). A qualitative investigation of the influence from CEP is desired. Another relevant factor affecting local L-shape recognition seems to consider the proportions between the area of one *L-branch-extensions* and the other *L-branch*, which is the ratio of area, where is shadowed over not shadowed (Fig.5 (c)). In order to figure out the relevant determining parameters affecting perception and cognition of L-shaped rooms using a haptic-audio interface, a systematic study is in preparation.



L-shape in #3
(a)

L-shape in #4
(b)

L-shape in #3
(c)

Fig. 5. Depictions for two L-shaped areas employed in the experiment

The results of global L-shape confirm the argument by Tversky that people do have inference ability based on the spatial information comprehended [17]. Such properties as the layout of the apartment and window configuration are supposed to affect the recognition of the global shape. When different rooms extend the apartment from the hallway towards obviously different directions, which is the case with floor plan #2, or when participants are provided with some clues of the concave edge of the entire global shape, such as the window configuration in floor plan #4a in Fig. 2, participants are more likely to recognize of the correct global shape. More specific research on the interaction of floor plan exploration and reasoning based on general knowledge about apartments and their standard layouts are planned for the future.

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