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Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind

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Abstract

Mental mapping of spaces is essential for the development of efficient orientation and mobility skills. Most of the information required for this mental mapping is gathered through the visual channel. People who are blind lack this information, and in consequence, they are required to use compensatory sensorial channels and alternative exploration methods. In this study, people who are blind use a virtual environment (VE) that provides haptic and audio feedback to explore an unknown space. The cognitive mapping of the space based on the VE and the subject's ability to apply this map to accomplish tasks in the real space are examined. Results show clearly that a robust and comprehensive map is constructed, contributing to successful performance in real space tasks.

Keywords: Blind; Cognitive mapping; Orientation rehabilitation; Haptic; Virtual reality

1. Introduction

Mental mapping of spaces and of the possible paths for navigating these spaces is essential for the development of efficient orientation and mobility (O&M) skills. Most of the information required for this mental mapping is gathered through the visual channel (Lynch, 1960). People who are blind lack this information, and consequently they are required to use compensatory sensorial channels and alternative exploration methods (Jacobson, 1993). The research reported here is based on the assumption that the supply of appropriate spatial information through compensatory sensorial channels, as an alternative to the (impaired) visual channel, may help to enhance blind people's ability to explore unknown environments (Mioduser, 2005) and to navigate in real environments.

The main goals of this study were to examine: (a) the exploration process of an unknown space using a multi-sensory virtual environment (VE), (b) the cognitive mapping process of an unknown space using the VE, and (c) the application of the constructed map for performing orientation tasks in the real space.

1.1. Background

Research on O&M in known and unknown spaces for people who are blind indicates that support for the acquisition of spatial mapping and orientation skills should be supplied at two main levels: perceptual and conceptual (Passini and Proulx, 1988; Ungar et al., 1996). At the perceptual level, visual information shortage is compensated by other senses, e.g., tactile or auditory information. Tactile and haptic information appear to be a main resource for supporting appropriate spatial performance for people who are blind. The word haptics derives from the Greek *haptikos* "able to touch". In his 1925 monograph *Der Aufbau der Taswelt* (The World of Touch), Katz coined the term "active touch" (Katz, 1989). Revesz (1950) continued this line of research focusing on the relationship between vision and haptic information for people who are blind in the context of philosophy and esthetics. For

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Revesz, the visual examination of a sculpture by a sighted person implies a holistic information collection process, comprising all sculpture's visual features. By comparison, haptic information is gathered progressively—different information is discovered during each phase of the exploration. Gibson, in 1962 (pp. 479), described active touch as "a concomitant excitation of receptors in the joint and tendons along with new and changing patterns in the skin. Moreover, when the hand is feeling an object, the movement or angle of each joint from the first phalanx of each finger up to the shoulder and the backbone makes its contribution". Haptic information is commonly supplied by the hands' palm and fingers (for fine recognition of object form, texture, and location), by the cane for low-resolution scanning of the immediate surroundings, and by the feet regarding surface information. The auditory channel supplies complementary information about events, the presence of other people (or machines or animals) in the environment, or estimates of distances within a space (Hill et al., 1993). The olfactory channel supplies additional information about particular contexts (e.g., perfumery, bookstore or bakery in a shopping center) or about people.

At the conceptual level, the focus is on supporting the development of appropriate strategies for an efficient mapping of the space and the generation of navigation paths. For example, Jacobson (1993) described the indoor environment familiarization process by people who are blind as one that starts with the use of a perimeter-recognition-tactic—walking along the room's walls and exploring objects attached to the walls, followed by a grid-scanning-tactic—aiming to explore the room's interior. Research indicates that people use two main spatial strategies: route and map strategies. Route strategy is based on linear recognition of spatial features, while map strategy is holistic and encompasses multiple perspectives of the target space (Fletcher, 1980; Kitchin and Jacobson, 1997). Fletcher (1980) showed that people who are blind use mainly route strategy when recognizing and navigating new spaces.

For a long period of time the information-technology devices that provided the blind person with information before her/his arrival to an environment were mainly verbal descriptions (VDs), tactile maps and physical models. Ungar et al. (1996) report on differences in the exploration performance of people who are blind using these technologies. Today, advanced computer technology offers new possibilities for supporting rehabilitation and learning environments for people with disabilities. Over the past 30 years, people who are blind have used computers supported by assistive technology (tactile or audio outputs). Tactile assistive technology includes devices such as the Optacon, which was invented by Linvill in 1963; tactile Braille displays; printers; tactile graphic displays (e.g., Nomad, Tdraw, Tguide); and tactile mouse (e.g., VirTouch and Moose; Wies et al., 2001). Audio assistive technology includes text-to-speech software and print-to-speech reading machines (e.g., Kurzweil's Reading Machine invented in 1976).

The exploration and learning of a new environment by people who are blind is a long process, and requires the use of special information-technology aids. There are two types of aids: passive and active. Passive aids provide the user with information before his/her arrival to the environment. Examples of these include VDs, tactile maps, strip maps, and physical models (Herman et al., 1983; Rieser, 1989; Ungar et al., 1996; Espinosa and Ochaita, 1998). Active aids provide the user with information in situ, for example, Sonicguide (Warren and Strelow, 1985); Kaspa (Easton and Bentzen, 1999); Talking Signs, embedded sensors in the environment (Crandall et al., 1995); virtual sound display (Loomis et al., 1998; Loomis et al., 2005); Personal Guidance System (PGS), based on satellite communication (Golledge et al., 1996; Golledge et al., 2004); and remote infrared audible signage and haptic pointer interface based on PGS (Marston et al., 2006). Research results on passive and active aids indicate a number of limitations that include erroneous distance estimation, underestimation of component sizes, low information density, or symbolic representation misunderstanding.

Virtual reality has been a popular paradigm in simulation-based training, in the gaming and entertainment industries. It has also been used for rehabilitation and learning environments for people with sensory, physical, mental, and learning disabilities (Schultheis and Rizzo, 2001; Standen et al., 2001). Recent technological advances, particularly in haptic interface technology, enable individuals who are blind to expand their knowledge by using an artificially made reality built on haptic and audio feedback. Research on the implementation of haptic technologies within VEs has reported on its potential for supporting the development of cognitive models of navigation and spatial knowledge with sighted people (Witmer et al., 1996; Giess et al., 1998; Gorman et al., 1998; Darken and Peterson, 2002) and with people who are blind as well (Colwell et al., 1998; Jansson et al., 1998). Strategies for the exploration and the collection of spatial information about a new area are different between sighted people and people who are blind. These strategies are based on the use of different perceptual information. The exploration process by sighted people is mainly based on the visual channel (Heller and Schiff, 1991), and for people who are blind the information is collected mainly using the haptic and audio channels. This study's results with people who are blind can be relevant for the use of VE applications for training sighted people in dark areas (firemen, army forces, or navy forces). Actually, in existing research on the use of VE for sighted people, the VE apparatus was based on multimodal output—visual and haptic or visual and audio (Gunther et al., 2004). However, the research results show that the additional audio or haptic outputs did not increase the subjects' spatial knowledge. It might increase their spatial knowledge only after special training on how to use effectively the other senses.

Related research on the use of haptic devices by people who are blind includes identification of textures and object shape (Colwell et al., 1998; Sjotrom and Rassmus-Grohn, 1999), mathematical learning environments and the exploration of mathematical graphs (Yu et al., 2001; Karshmer and Bledsoe, 2002), the exploration of geography maps using audio and tactile feedback (Parente and Bishop, 2003), and the construction of cognitive maps (Sanchez and Lumbreras, 1999; Lahav and Mioduser, 2000; Semwal and Evans-Kamp, 2000).

The research reported in this paper aimed to examine the contribution of the work with a haptic-based VE to the exploration process, and the construction of cognitive maps, of an unknown space by blind subjects. The main research questions in this study were

1. What strategies and processes people who are blind do use for exploring an unknown space?
2. What structural components and relationships among them are included in the cognitive map constructed by people who are blind, who explored the unknown space in the VE, compared to people who explored directly the real space?
3. How does the constructed cognitive map contribute to the blind person's performance in orientation tasks in the real space?

The rest of the paper is organized as follows. In the next section, we will briefly describe the VE that was developed specially for this study. Next we will present the research method. We will then present the experimental results and conclude with a discussion on these.

2. The virtual learning environment

For the study we developed a multi-sensory VE modeling real spaces. The user interacted with the VE using a Microsoft® SideWinder Force Feedback Joystick (FFJ). By using the FFJ the user could move within the VE and feel an object's texture, location, and size. This system comprises two modes of operation: developer and learning.

The core component of the developer mode is the VE editor. This module includes three tools: a *3D environment builder* used to define the physical characteristics of the space such as the type and size of components (e.g., doors, windows, furniture pieces) and their location, an *haptic feedback editor* used to attach force-feedback effects to all the VE's components, and an *audio feedback editor* used to attach auditory information to the objects (e.g., its name, tapping or bumping sounds, alerts when corners are reached, footsteps). The sound interval of the footsteps indicates the speed of the navigation, and the user's stride-length is the benchmark for distance in the virtual scene.

The learning mode, within which the learner works, consists of the simulated space to be navigated by the users using the FFJ (Fig. 1) and additional features that serve teachers during and after each learning session. For example, on-screen monitors present real-time information on the user's navigation performance (e.g., position or objects already reached). An additional feature allows the teacher to record the participant's navigation path and replay it to analyze and evaluate the participant's performance (Fig. 2).

During the development stage a preliminary evaluation of the VE was conducted in the form of a case study of a blind person's working process with the force-feedback-based tool. The goal of this evaluation was to collect information on five main aspects: user's response to FFJ, the type of force feedbacks that strongly affected his navigation performance, the user's ability to identify structural features of the environment and the objects in it, the user's ability to navigate the VE, the user's ability to

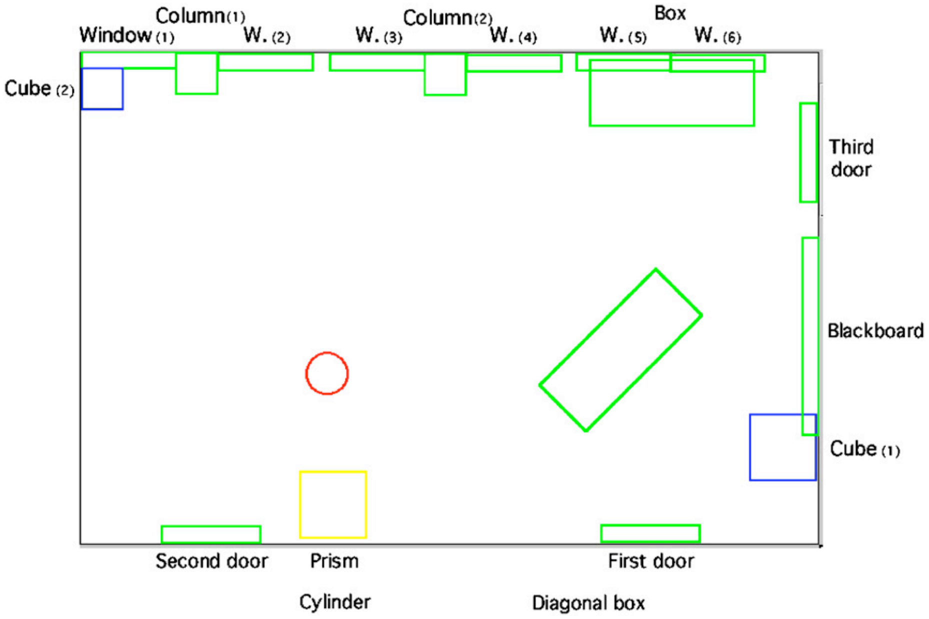
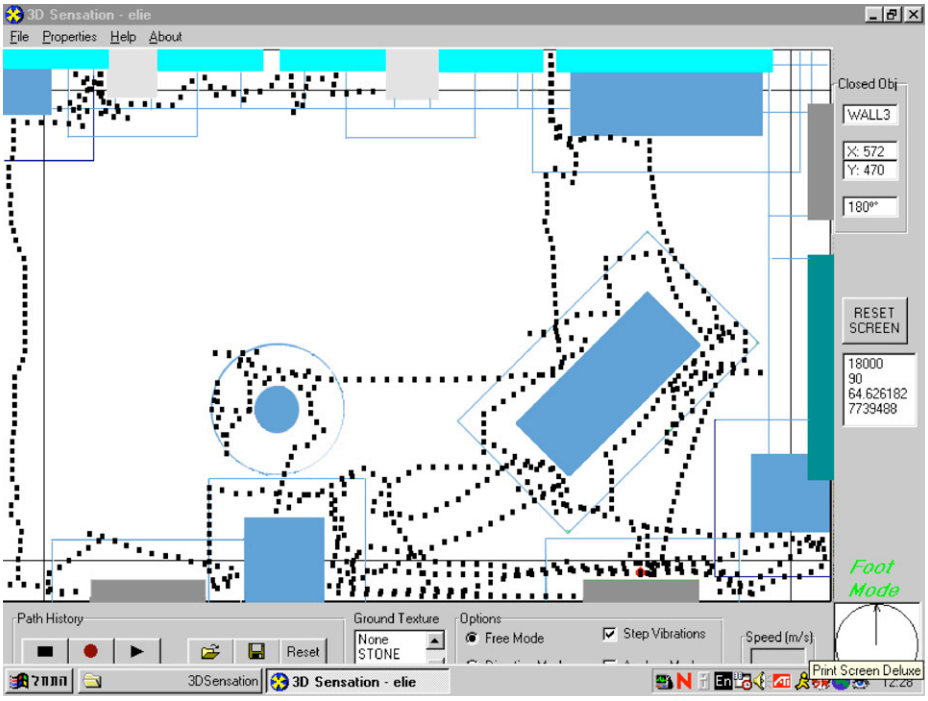


Fig. 1. The virtual environment.



Closed Obj: WALL3
X: 572
Y: 470
180°
18000
90
64.626182
7739488
Ground Texture: None STONE
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Fig. 2. Recorded log and monitoring data.

construct a cognitive map of the simulated room, and the user's ability to navigate the real environment. A detailed presentation of the findings of the preliminary evaluations can be found in Lahav and Mioduser (2003).

3. Method

3.1. Subjects

The study included 31 participants who were selected on the basis of seven criteria: total blindness (without any visual ability), at least 12 years old, not multi-handicapped, received O&M training, Hebrew speakers, onset of blindness at least two years prior to the experimental period, and comfortable with the use of computers. All the participants reported no previous experience with VEs or FFJ. The participants ranged in age from 12–70 years old (see Table 1), being mostly adults in the age range of 24–40; 17 participants were congenitally blind and 14 late blind; 17 female and 14 male.

We defined two groups that were similar in age, age of vision loss (congenitally blind or late blind), and gender. The experimental group included 21 participants who explored the unknown space by means of the VE. The control group included 10 participants who explored the unknown space by actual navigation in the real space. To evaluate the participants' initial O&M skills, all were asked to individually complete a questionnaire on O&M issues. The results showed no differences in initial O&M ability among participants in both groups.

Table 1 summarizes the information about the research participants by the different characteristics considered: group, age, age of vision loss, and gender.

3.2. VE research instruments

The research included nine instruments, three for the implementation and six for the collection of the data. The three instruments for the *implementation* of the study were:

Unknown space, real and simulated: The real space was a 54-square-meter room with three doors, six windows and two columns. There were seven objects in the room, five of them attached to the walls and two placed in the inner space (see Fig. 3). We chose this environment because we wanted to use a relatively simple space for this first systematic study, yet enabling us to ask the participants to perform within it a variety of complex orientation tasks. This real space was virtually represented in the computer environment (see Fig. 1 above).

Exploration task: Each participant was asked to explore the VE individually and without time limitations. The experimenters informed the participants that they would be asked to describe the room and its components at the end of their exploration.

Orientation tasks: Each participant was asked to perform two orientation tasks in the real space: a target-object task and a perspective-taking task. In the target-object task, the participant was asked to find an object in the space (e.g., *Reach and identify the basket located upon the large box*). In the perspective-taking task, the participant entered the room from a different entrance and was asked to find an object in it (e.g., *Walk from the distant door to the cylinder*).

In addition, a set of six instruments was developed for the *collection* of quantitative and qualitative data:

O&M questionnaire: The questionnaire had 46 questions about the participant's O&M ability indoors and outdoors, in known and unknown environments. Some of the

Table 1
The study's participants

Group	Age		Age of vision loss		Gender	
	Adult	Teenage	Congenitally blind	Late blind	Female	Male
Experimental group ($N = 21$)	15	6	11	10	11	10
Control group ($N = 10$)	8	2	6	4	6	4


Fig. 3. The real environment.

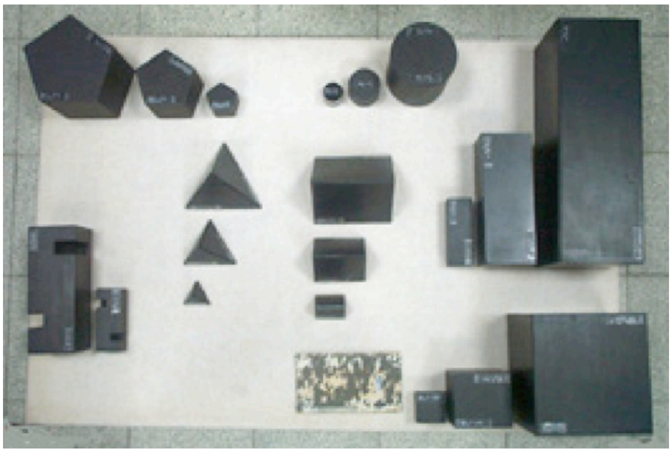
Fig. 4. The physical model building kit components.

questions were adapted from O&M rehabilitation evaluation instruments for use in this study (e.g., a preschool O&M screening by Dodson-Burk and Hill, 1989; Sonn et al., 1999; and a rehabilitation evaluation by the rehabilitation center of the Israeli Lighthouse). The aim of this questionnaire was to evaluate the participants O&M ability in a variety of real spaces and to find differences and similarity in their O&M experience and abilities. The O&M questionnaire included four parts: (a) 19 descriptive questions (e.g., age, gender, age of vision loss); (b) eight questions on the subject's O&M ability in known indoor environments (e.g., home, school, work, etc); (c) 12 questions about the subject's O&M ability in known outdoor environments (e.g., street crossing, using public transportation, walking in shopping centers, etc); (d) seven questions on subject's O&M ability in unknown indoor environments (e.g., what are the O&M devices you use in unknown indoor environments?, next week you are going to move to a new office or classroom. You will be visiting the new place today. What do you need to do to ensure yourself appropriate orientation in the new space next time?). Among the questions 23 O&M-related questions were answered in a four-level ability scale: (i) I cannot do the task, (ii) I need assistance from a sighted person, (iii) I need to use an O&M device, (iv) I can do the task independently.

Observations: The participant's exploration and task performances in the real space were video-recorded.

Open interview: After completing the exploration task, the participants were asked to describe the space verbally. This open interview was video-recorded and transcribed.

Modeling-kit: The modeling-kit was used by the participants to construct a physical model of the space. The kit comprised: (a) three alternative options for the room's structure (e.g., by its form, dimensions, walls, number of windows and doors); (b) eight plastic objects, five corresponding to the ones actually in the research environment (cube, box, cylinder, prism), three distracting objects (pyramid and special types of boxes) and blackboard. The objects were offered in three different sizes (50%, 100%, and 200%) in relation to their original scale-size (see Fig. 4). The 22 building blocks were labeled in Braille and had a Velcro strip so they could be attached to the carpet in the model's floor. In previous studies, researchers have used similar modeling kits made of wooden blocks (Passini and Proulx, 1988; Kitchin and Jacobson, 1997).

Computer log: The computer data enabled the researchers to track the user's exploration activities in the VE in two ways: as a text file containing precise spatial and temporal data and as a visual reconstruction (a sort of "film") of the participant's movements within the virtual space. The integration of both sets of data supplied information about the users' exploration strategies, distances traversed, path duration, switch of strategies, and pauses (see Fig. 2).

Evaluation and coding schemes: Two O&M rehabilitation specialists who have been working in a rehabilitation center for people who are blind for more than 15 years took part in the evaluation process, e.g., in the design and construction of each coding scheme based on the observation of video data and user logs; the identification and classification of exploration strategies; the consolidation of evaluation instruments based on the previous analyses and on the O&M literature (e.g., Jacobson, 1993; Jacobson et al., 1998); the implementation of the instruments for analyzing the participants' O&M exploration, performance, and acquaintance with the new space. The design and construction process of the coding schemes included four stages. In the first stage, based on the observation of video movies and user logs, each specialist collected and classed the various exploration strategies used by people who are blind during their exploration of the new space. In the second stage, a unified coding scheme was synthesized using the experts' analyses as well as results reported in the O&M literature (e.g., Jacobson, 1993; Jacobson et al., 1998). After this stage the O&M specialists evaluated the coding scheme by applying it in analyzing a sample of video movies and user logs. Finally, in the actual evaluation stage of the participants' data, the O&M specialists used this instrument to analyze their O&M performance and acquaintance process with the new space. Each O&M specialist observed independently the users' logs or video and coded the data. Agreement in the experts' evaluations was achieved for 23 cases (out of 31). A third O&M expert was recruited to complete the evaluation process of the data of the remaining eight cases.

3.3. Procedure

All participants worked and were observed individually. The study was carried out in six stages. First, all the research participants were asked to individually complete an O&M questionnaire. In the second stage, the experimental group became acquainted with the VE's components and operation modes. The series of tasks administered at this stage included free navigation, directed navigation, and a task aimed to introduce the auditory feedback. This stage lasted about 3 h (two meetings). The next stage focused on the participants' exploration of the unknown space, either real or virtual. Following the exploration, the participants were asked to give a VD of the space and to construct a physical scale model of it using the modeling-kit. This stage lasted about 1.5–2.5 h and was video-recorded. After this stage the participants were asked to perform two orientation tasks in the real space. This stage lasted about half an hour. The last stage includes processing and analysis of the collected data.

4. Results

Research Question 1: *What strategies and processes people who are blind do use for exploring an unknown space?*

Six aspects are of interest as regards to the *exploration processes* used in the two groups: the exploration strategies, the duration of the exploration, the distance traversed, the number of switches among strategies, the sequence of implemented strategies, and the number and kinds of pauses made while examining the new space.

Results show that participants in both groups implemented similar exploration strategies, mostly based on the ones they used in their daily navigation in real spaces. Examples of strategies implemented are: "perimeter", e.g., walking along the room's walls and exploring objects attached to the walls (see Fig. 5, Route 1); "grid", e.g., exploring the room's inner-space (see Fig. 5, Route 2); "object-to-object", e.g., walking from one object to another (see Fig. 5, Route 3); "points-of-references", e.g., walking in the environment and creating landmarks (see Fig. 5, Route 4). However, an interesting additional finding is that several participants in the experimental group developed new strategies while working within the VE. One example is a "constant scanning" strategy by which the participant collects information about the room's interior while collecting perimeter information (somehow resembling the use of a long cane in real space—as shown in Fig. 6, Routes 1 and 2). These new strategies could be generated only within the VE, representing an important added value of the work with the computer system.

As already mentioned, no statistically significant difference between groups was observed as regards the types of strategies used, the frequency of use of the strategies, and

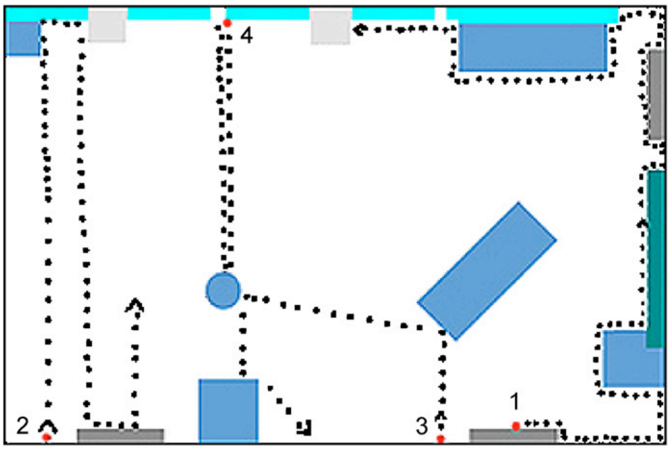

Fig. 5. Exploration strategies.

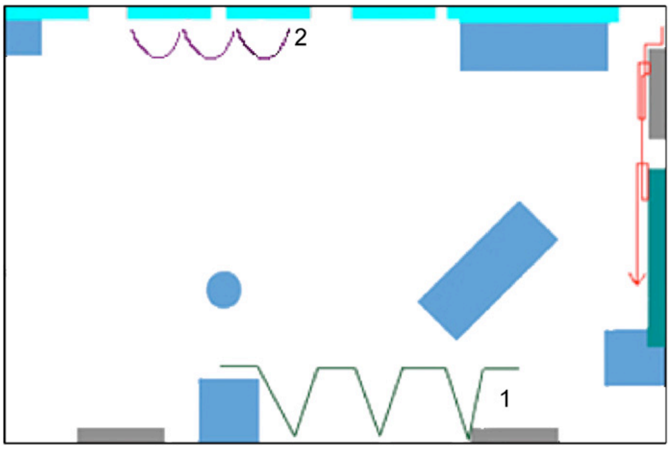

Fig. 6. New exploration strategies.

concerning the distance traversed using each strategy. Data in Table 2 indicate that the strategy most frequently used by the experimental group was "grid", followed by the "perimeter" strategy. In contrast, the control group preferred to explore the room's perimeter, and next to use the object-to-object strategy. Examining the distance traversed using each strategy, we found that both groups' participants traversed the longest distance using the "perimeter" strategy. The experimental group made frequent switches of strategy during their walk.

Concerning the duration of the exploration, it should be noted that the participants were not limited in time for accomplishing the task. Participants from the experimental group needed an average of four times more time to explore the new environment ($M = 38$ min) than the ones from the control group ($M = 10$ min). This difference was significant ($t(28) = 7$, $p = 0.000$). Significant difference has been found also for the total length of the exploration path ($t(29) = 5.44$, $p = 0.000$). Participants in the experimental group traversed a distance average of three times more ($M = 256$ m) than the control group participants ($M = 96$ m), see Table 3.

The experimental-group participants made frequent switches of strategy during their walk in the VE, in contrast with the control-group participants' performance in the real space. This behavior is reflected in the total and average frequency of use of the various strategies by both groups (see Table 3): total frequency of 297 ($M = 14$) for the experimental group, and total frequency of 65 ($M = 6.5$) for the control group.

Significant difference was also found between the groups in the sequence of main strategies implemented ($\chi^2(2) = 7.55$, $p < 0.05$). Most experimental-group participants (62%) used the grid strategy first and then the perimeter strategy. In contrast, most control-group participants (90%) preferred first to explore the room's perimeter and then the objects located in the inner space of the room.

Participants from both groups made many pauses during their walk, suggesting that different cognitive operations related to the task in process were activated during these intervals. In terms of duration and function, we defined two types of pauses: short and long. Short pauses (4–10 s) were used for technical purposes (e.g., changing the hand that holds the force-feedback joystick) or for reflection on a recent action. Long pauses (more than 10 s) were used for memorizing spatial information, reflection on a recently implemented exploration strategy, or planning. As shown in Table 3, significant difference was found between the groups ($t(26) = 7.65$, $p < 0.001$; $t(25) = 2.56$, $p < 0.05$) for both short and long pauses. The experimental group made about three times more long pauses, and six times more short pauses. No time limit was given to either research populations to explore the environment, and each subject decided individually how much time he or she was willing to invest on the exploration process. Possibly the work within the VE system motivated the subjects to spend much more time in the exploration. The ability to collect spatial information in a safe environment and in game mode encouraged the experimental subjects to interact with the

Table 2
Exploration strategies, frequency and length

Exploration patterns	Experimental group ($N = 21$)		Control group ($N = 10$)	
	Frequency	Length of the path (in meters)	Frequency	Length of the path (in meters)
Perimeter	86	2155	28	698
Grid	116	1052	9	46
Object to object	27	389	14	109
Points of reference	50	1063	13	85
Scanning area	–	–	1	27
New strategies	18	728	–	–
Sum	297	5387	65	965

Table 3
Research participants' average of aspects as regards to their exploration processes

	Experimental group ($N = 21$)	Control group ($N = 10$)	
The duration of the exploration strategies (min)	38	10	*
The distance traversed (m)	256	96	*
Strategies frequency	14	6.5	
Long pauses	17	6	**
Short pauses	81	13	***

*$p < 0.000$.
**$p < 0.05$.
***$p < 0.001$.

VE components, to investigate them, and to reflect on the VE structure, components and their interactions with it.

As the above results indicate,

Table 5
Participants' description of structure's components

	Experimental group ($N = 21$)	Control group ($N = 10$)
Doors	–	2 20%
1st door	15 71%	2 20%
2nd door	9 43%	4 40%
3rd door	5 24%	3 30%
Windows	7 33%	5 50%
1st window	7 33%	–
2nd window	3 14%	–
3rd window	7 33%	–
4th window	6 29%	–
5th window	5 24%	–
6th window	4 19%	–
Columns	3 14%	–
1st column	10 48%	–
2nd column	10 48%	–

the creation of spatial references, direction-towards-other-objects estimation, and distance estimation. The participants included expressions or gestures indicative of their ability regarding these aspects in their VDs and models.

The average number of expressions denoting spatial references (e.g., "if you walk near the right wall, you can find the first cube attached to that wall and then there is the blackboard and the third door") was significantly higher in the descriptions from the experimental group than from the control group ($t(29) = 2.49$, $p < 0.05$). The average number of direction-estimation expressions (e.g., "left, closer to the left wall, you can find the second door") was similar in both groups. Only a few expressions related to distance-estimation (e.g., "between the two doors, closer to the door…right to the second door you can find the prism") were included in descriptions from participants in both groups. These findings suggest that participants in the experimental group showed a high ability to identify not only the individual objects within the space, but also the configuration of locations of these objects relative to each other.

The cognitive-map construction process variables were reflected in the participant's VDs. The participants used four types of spatial-description-templates to describe the environment: perimeter description, object-to-object description, items-list, and description from the entrance-door point of view. The most frequent templates used by participants in the experimental group were perimeter description and object-to-object description, and the most frequent template in the control group was the item-list description. To further categorize, participants in the experimental group used procedural descriptions while the control group used mainly declarative descriptions. The use of procedural templates indicates that both the building and the recall of the cognitive map were perceived by the experimental group participants as a construction process in which they are actively involved, a process that is subjectively enacted rather than objectively described. In addition, these results could be explained by egocentric and allocenteric spatial encodings. Egocentric define by the way the subject described the space by involving himself (body or functional behavior) as the origin of the space within the objects are located. The allocentric defined by the way the subject described the space by using one of the space components (structure or objects). Our research results show that the experimental group relies more on allocentric encoding and the control group relies more on egocentric encoding.

The frequency of use of the different spatial strategies was evenly distributed within the experimental group, with minor predominance of route model strategy. In the control group, the map model strategy was predominant, an indication of the differential character of the processes (procedural or declarative) elicited by the spatial exploration in either virtual or real spaces. Examining the sequence of items mentioned in the VDs, we observed a significant difference between the groups ($\chi^2(1) = 10.60$, $p < 0.005$). Most participants in the experimental group (81%) chose to describe the room's structure first and later to describe its content. In contrast, the participants in the control group preferred to describe the content components first and the room's structure later on.

Research Question 3: *How does the constructed cognitive map contribute to the blind person's performance in orientation tasks in the real space?*

Following the construction of the cognitive map the participants were asked to perform two orientation tasks in the real space: a target-object task and a perspective-taking task. In the target-object task the participants were asked to: 'Reach and identify the basket located on the box', and in the perspective-taking task, the participants were asked to enter the room from a different entrance door and to: 'Walk from this door to the cylinder'. It should be recalled that the experimental group participants entered the real space for the first time to perform the tasks, and were not given the option to first explore the room (initial exploration was accomplished in the VE only). Five variables were examined as regards to the *performance in orientation tasks in the real space*. The variables included: successful completion of the tasks, use of direct paths to the target location, time spent on task, number and duration of pauses (short pauses and long pauses), and total length of the path. Most of the participants in the experimental group successfully performed both orientation tasks in the

Table 6
Participants' descriptions of room's objects (percentage of participants, by group)

Objects		Experimental group ($N = 21$)				Control group ($N = 10$)			
		Object mention (%)	Object location (%)	Object size (%)	Object placement (%)	Object mention (%)	Object location (%)	Object size (%)	Object placement (%)
Cube 1	VD	67	67	–	–	40	40	–	10
	Model	86	34	48	71	30	50	30	30
Cube 2	VD	76	62	–	–	50	30	–	–
	Model	95	57	43	81	70	10	60	30
Box	VD	67	48	–	5	80	50	–	30
	Model	76	43	24	62	70	40	70	50
Diag. box	VD	91	71	5	14	60	60	10	20
	Model	91	48	52	91	60	40	30	60
Cylinder	VD	71	52	–	–	40	30	–	10
	Model	71	43	38	71	40	40	40	20
Prism	VD	91	67	–	–	60	50	–	–
	Model	100	43	62	48	70	40	30	50
Blackboard	VD	62	57	–	–	20	10	–	–
	Model	67	52	–	57	20	20	20	20
Total (Mean)	VD	75	61	0.7	3	53	40	3	10
	Model	84	46	48	69	48	28	29	27

Table 7
Qualities of real-space orientation tasks' completion—target-object task

		Experimental group ($N = 21$)	Control group ($N = 10$)	
Extent of success	Succeeded	17 (81%)	4 (40%)	*
	Needed assistance	3 (15%)	6 (60%)	
	Failed	1 (5%)	–	
Performance path	Direct path	14 (67%)	3 (30%)	**
	Indirect path	6 (29%)	7 (70%)	
	New exploration	1 (5%)	–	
Total duration (seconds)		66	118	
Total distance (meters)		28	47	***
Short pauses		3	6	
Long pauses		1.5	2.7	

*$\chi^2(2) = 7.02$, $p < 0.05$.
**$\chi^2(3) = 8.20$, $p < 0.05$.
***$p < 0.05$.

Table 8
Qualities of real-space orientation tasks' completion—perspective-taking task

		Experimental group ($N = 21$)	Control group ($N = 10$)
Extent of success	Succeeded	15 (71%)	6 (60%)
	Arrived close to the target	5 (24%)	2 (20%)
	Failed	1 (5%)	2 (20%)
Performance path	Direct path	8 (38%)	3 (30%)
	Indirect path	7 (34%)	3 (30%)
	New exploration	6 (29%)	4 (40%)
Total duration (seconds)		153	191
Total distance (meters)		86	95
Short pauses		3	5
Long pauses		1.5	3

real space. Significant difference was found between the groups in the target-object task, for the following variables: successful completion of the task ($\chi^2(2) = 7.02$, $p < 0.05$), use of direct paths to the target location ($\chi^2(3) = 8.20$, $p < 0.05$), and total length of the path traversed ($p < 0.05$) (see Table 7). Most participants of the experimental group successfully performed the target-object task while choosing a more direct and shorter path than the control group participants, more than half of the experimental group participants (67%) chose a straight walking path.

When examining the perspective-taking task, most participants of the experimental group successfully performed the task in shorter time and path length than the control group, as presented in Table 8.

The results are clearly indicative of the contribution of learning with the VE to the participants' anticipatory mapping of the target space and consequently to their successful performance in the real space. Moreover, they show that such a mapping resulted in the experimental group's greater capability in performing the real-space tasks.

5. Discussion

The results of this study helped us to elucidate several issues about the contribution of working within a VE for the learning process of unknown spaces for people who are blind, their ability to construct a cognitive map of it, and to apply this map for navigating in the real space.

5.1. Exploration strategies and processes in the VE

The study's results suggest that the work within the VE gave the participants a stimulating, comprehensive, and thorough acquaintance with the target space. The participants were able to collect rich and varied information about the environment at different resolution levels, and re-evaluate (in recurrent scanning movements) the information already gathered.

The system's flexibility allowed the participants to transfer exploration strategies commonly used by them in real spaces into their investigation of the unknown space in the VE. The use of "real exploration strategies" in VEs was reported in previous studies on spatial performance with sighted participants (Witmer et al., 1996; Darken and Peterson, 2002). In addition, however, this study's participants applied the known strategies in novel ways. For example, they preferred to explore the inner part of the room first and only then its boundaries (in contrast with the exploration patterns described by Jacobson, 1993). Moreover, they created new exploration strategies, such as the one simulating walking with a white cane following the perimeter of the room and at the same time exploring each segment's corresponding inner areas. This simultaneous-exploration strategy is only possible within the VE.

Comprehensive exploration of the unknown space in the VE required time. Similar results were reported in previous studies. Darken and Peterson (2002) and Waller et al. (1998) compared sighted participants' exploration of spaces by means of VE, other information-technology spatial devices, and directly in the real space, finding that exploration in the VE demanded the longest time. However, they also found that the longer duration of the exploration in the VE affected the participants' performance in the real space: they performed better than participants exposed to other spatial exploration devices. It is reasonable to expect that exploration time will become shorter as participants gradually get used to work with VE systems as learning tools.

5.2. Construction of a cognitive map as a result of exploring the VE

The findings of the present study provide evidence of transfer from the exploration within the VE to the cognitive map constructed. Descriptions included spatial references clearly based on the VE's components and landmarks.

In addition, we found that salient features of the VE contributed to overcoming difficulties in spatial mapping reported in previous research, e.g., the objects' dimensions. Colwell et al. (1998) conducted a study that described people who are blind's difficulties in identifying complex objects and estimating sizes of large objects using a PHANToM® haptic device. Similar distance estimation difficulties were observed in the use of tactile maps, models and VDs for learning about unfamiliar spaces (Ungar et al., 1996). In the VE used in this study, auditory feedback supplied at different levels (e.g., the name of an object, indication that its end was reached, indication of turning points), and haptic feedback helped the participants map the object's identity, form and dimensions with little effort. Thus, major cognitive resources could be allocated to the mapping of overall spatial features and relationships in the explored space. It should be noted that in its current version, the VE did not include explicit measuring tools that could assist in estimating an object's actual dimensions and distances among spatial components. Additional research is needed to assess the contribution of such quantitative data into the constructed cognitive maps.

We did not observe a predominance of particular description strategies among the participants, as has been reported in previous studies. For example, Fletcher (1980) found spatial-description-strategy differences between congenitally and late blind. In this study each participant tended to describe the space using different spatial description strategies, and no difference was observed among subgroups (e.g., by age-of-vision-loss, age, gender).

5.3. Performance of orientation tasks in the real space as a result of exploring the VE

The participants' success in performing the orientation tasks in the real space demonstrate their ability to transfer spatial knowledge gathered solely in the VE (and cognitively mapped in correspondence) into the real space. We found much evidence of the robustness of the constructed map and its contribution to the participant's performance in the real space.

Whether people are blind or sighted, walking in an unknown environment for the first time is usually slow and hesitant. For exploring an unknown environment, people who are blind use mostly the perimeter strategy (Jacobson, 1993). In contrast with these observations, in their very first walking experience in the real space after having explored the room virtually, this study's participants walked into the inner room confidently and decisively.

Previous research results on the contribution of preliminary exploration prior to entering real spaces are not conclusive. A study with sighted people exploring a virtual and a real space showed that the spatial performance of those who explored the virtual space was poorer than that of those who explored the real space (Witmer et al., 1996). In contrast, Thorndyke and Hayes-Roth (1982) found that participants were able to navigate better in the real space after being exposed to tactile maps or VDs than after learning its features by direct exploration. Our findings reinforce the claim that prior exploration—and anticipated cognitive mapping—of unknown spaces contributes to the subsequent performance in the real space.

In this study one example of the cognitive map's contribution to the participants' performance is their frequent use of the object-to-object strategy in real space tasks, reported in previous research as frequently used by successful navigators (e.g., Hill et al., 1993; Golledge et al., 1996).

A second example is the participants' level of success in performing perspective-taking tasks, contrasted with previous reports on (both blind and sighted) peoples' difficulties and unsuccessful performance in those tasks (e.g., Rieser, 1989; Munro et al., 2002). Our research results unveil the complex ability developed by the participants to manipulate the cognitively mapped spatial information and to proceed confidently and successfully to the target.

5.4. *Implications of the study*

This study's results have implications for both research and implementation purposes. In future research, examples of additional variables to be considered are: a deeper examination of the causes of the long exploration time required within the VE; the mapping process of different kinds of environments, e.g., indoor or outdoor spaces, complex public spaces (such as campuses, museums, shopping centers), and irregular surfaces; or the mapping process of different resolution and granularity levels of spatial information and its contribution to performance.

At the implementation level, as haptic devices are rapidly becoming affordable for individual use, this study's insights might be applied for different purposes. One possible application is for supporting the acquisition of O&M skills and strategies by late blind as part of their rehabilitation in centers or by distance learning. At another level, the development of a variety of models of spaces (e.g., public buildings, shopping areas) will enable pre- and post-actual-visit exploration and mapping of unknown spaces by people who are blind, similar to sighted peoples' use of diverse map systems (e.g., Mapquest, Yahoo Maps). Previous research (Marston et al., 2006) express the O&M opportunities for people who are blind and to increase the quality of life. In a different application area, the development of haptic-based tools for supporting learning processes in K-12 academic curriculum subjects (e.g., for learning physics, geometry, and other academic subjects) can be advanced.

Additional research and development efforts will transform this promising technology into useful learning and support tools for a varied range of populations with special needs.

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