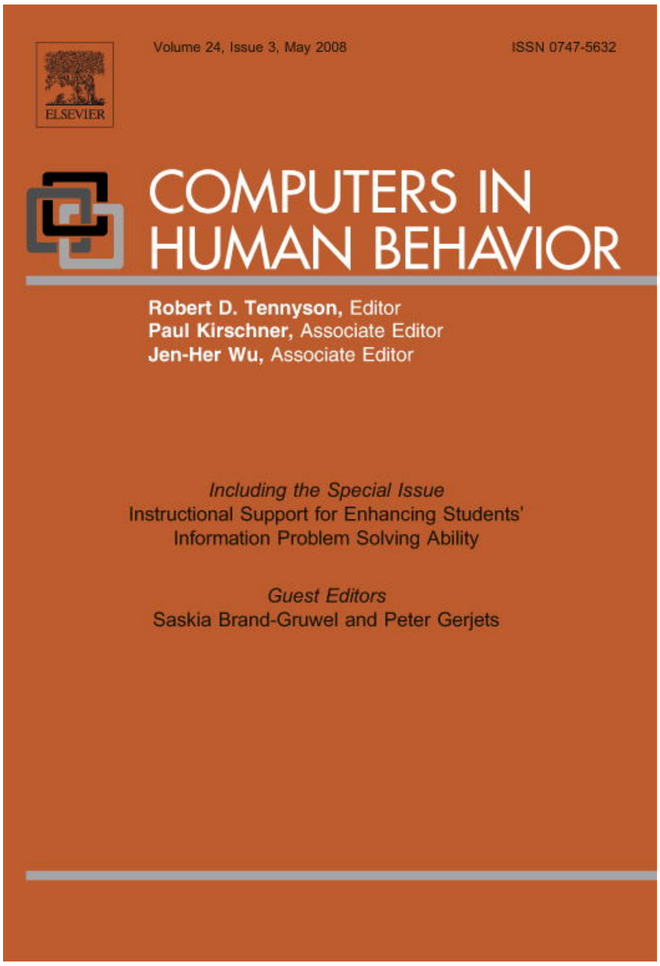
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Construction of cognitive maps of unknown spaces using a multi-sensory virtual environment for people who are blind

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Abstract

Most of the information used by people for the cognitive mapping of spaces is gathered through the visual channel. People who are blind lack the ability to collect the required visual information either in advance or *in situ*. This study was based on the assumption that the acquisition of appropriate spatial information (perceptual and conceptual) through compensatory sensorial channels (e.g., haptic) within a virtual environment simulating a real target space may assist people who are blind in their anticipatory exploration and cognitive mapping of the unknown space. The two main goals of the study were: (a) the development of a haptic-based multi-sensory virtual environment enabling the exploration of an unknown space and (b) the study of the cognitive mapping process of the space by people who are blind working with the multi-sensory virtual environment. The findings suggest strong evidence that the work within the multi-sensory virtual environment provided a robust foundation for the participants' development of comprehensive cognitive maps of the unknown space.

1. Introduction

Confident orientation and mobility (O&M) performance is facilitated by the possession of a robust cognitive map of the space being navigated and its defining features, e.g., overall structure, spatial components, landmarks, dimensions, and relative positions.

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Most of the information used by people for the cognitive mapping of spaces is gathered through the visual channel (Lynch, 1960). In addition, before navigating an unknown space people often collect information using resources such as maps, pictures, or drawings. People who are blind lack the possibility to collect this crucial visual information, either in advance or *in situ*, and in consequence, they are required to use compensatory sensorial channels and alternative exploration methods (Jacobson, 1993). Moreover, the obtainment of substantial information and cognitive mapping of an unknown space *before* arriving to it appears to be crucial for supporting secure O&M performance for people who are blind.

Previous research on mobility in known and unknown spaces for people who are blind (Golledge, Klatzky, & Loomis, 1996; Ungar, Blades, & Spencer, 1996) indicates that support for the acquisition of spatial mapping and orientation skills should be supplied at two main levels: perceptual and conceptual. At the perceptual level, the deficiency in the visual channel should be compensated with information supplied via other senses, e.g., hearing, smell or touch. As for the conceptual level, the focus is on supporting the development of appropriate spatial strategies for the efficient exploration of a space and the generation of efficient navigation paths. For example, Jacobson (1993) described indoor environment spatial strategies for people who are blind as those that start with the use of a perimeter-recognition tactic (such as walking along the room's walls and/or exploring objects attached to the walls) followed by a grid-scanning tactic to explore the room's interior. Research indicates that people use two main spatial strategies: route strategies 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 & Jacobson, 1997). In his research Fletcher (1980) shows that people who are blind use mainly route strategy when recognizing and navigating new spaces. Similarly with structural components, which are based on visual information that allows sighted people to construct a cognitive map (Lynch, 1960), people who are blind use alternative channels such as auditory and tactile. These components are based on spatial landmarks and clues (Ambrose, 2000; Long & Hill, 1997). Our study is based on the assumption that the supply of appropriate spatial information (perceptual and conceptual levels) through compensatory sensorial channels, as an alternative to the visual channel, may assist people who are blind in their anticipatory exploration and cognitive mapping of unknown spaces (Mioduser, 2005).

Information technologies can be a great help in gathering spatial information for people who are blind. This population currently uses two types of information-technology devices: (a) passive devices that provide spatial information before arrival to the environment, e.g., verbal descriptions, tactile maps, physical models, and (b) dynamic devices that provide spatial information *in situ*, e.g., Sonic-guide (Warren & Strelow, 1985), "Talking Signs" embedded in the environment (Crandall, Bentzen, Myers, & Mitchell, 1995), the "Kaspa" laser-guided device (Easton & Bentzen, 1999), or the "Personal Guidance System" based on satellite communication (Golledge et al., 1996).

There are a number of limitations and constraints, however, in the use of these devices. For example, the limited dimensions of tactile maps and models may result in poor resolution of the spatial information provided, and they might lack precise topographical features or accurate dimensions and location for structural objects. More advanced technologies often demand logistic arrangements that have difficulty with scalable implementation. For example, sensors or real-time information-supply devices would need to be installed in all spaces that would be navigated by people who are blind. In an effort to address these limitations, the study reported here focused on the supply of essential spatial information about unknown environments through the use of a virtual navigation system *before* arrival to the new space.

Advanced computer technology comprises visual, audio, and haptic features. Haptics is defined in the Webster dictionary (Webster, 1983) as: 'of, or relating to, the sense of touch.' Sailsbury and Srinivasan (1992) define haptics as: "manual interactions with the environment…that involves acting on the physical environment as well as sensing it." For people who are blind, haptic information is commonly supplied by the cane for low-resolution scanning of the immediate surroundings, by palms and fingers for fine recognition of an object's form, texture and location, and by the feet for surface information. The use of advanced haptic technologies offers new possibilities for learning or rehabilitation processes in special needs populations, serving either as assistive or adaptive aids. Current virtual reality (VR) technology facilitates the development of rich virtual models of physical environments and objects to be manipulated, offering people who are blind the possibility to undergo learning or rehabilitation processes without the usual constraints of time, space, and the massive demand of human tutoring (Loomis, Klatzky, & Golledge, 2001; Schultheis & Rizzo, 2001; Standen, Brown, & Cromby, 2001). Research on the implementation of haptic technologies within VR spatial simulation environments reports the potential for VR to support cognitive map construction training with sighted people (Darken & Banker, 1998; Darken & Peterson, 2002; Waller, Hunt, & Knapp, 1998; Witmer, Bailey, Knerr, & Parsons, 1996) and perception of virtual textures and objects by people who are blind (Colwell, Petrie, & Kornbrot, 1998; Jansson, Fanger, Konig, & Billberger, 1998).

The larger study addressed questions related to the contribution of learning about an unknown space within a multi-sensory virtual environment (MVE), on the actual O&M performance of people who are blind in the real space. The study focused on their ability to explore and learn with the MVE (Lahav & Mioduser, 2004), the mental modeling process, the implementation of the cognitive model while performing the real space tasks (Lahav & Mioduser, submitted for publication), or differences in mental modeling and performance by variables such as age, congenital or late-blindness, and dominant exploration strategies. In the present study, we report on the contribution of navigating the MVE to a blind person's construction of efficient cognitive maps of unknown spaces.

The specific research questions of this study were:

1. What *structural components and relationships* are included in the cognitive maps generated by people who are blind who explored the space in either virtual or real modes?
2. What are the characteristics of the *cognitive mapping process* by people who are blind who explored the space in either virtual or real modes?

Before reporting on the study's results and conclusions, we will briefly describe the main features of the MVE.

2. The haptic virtual environment

The MVE developed for this study comprises two modes of operation: Developer/Teacher mode and Learning mode. The core component of the Developer/Teacher mode is the virtual environment editor, which includes three tools: (a) environment builder, (b) force feedback effects editor, and (c) audio feedback editor. By using the environment editor the developer can define the physical characteristics of the space, such as size and shape of the room, or type, size and location of the objects (i.e., doors, windows and furniture). Using the force feedback effects (FFE) editor the developer is able to attach haptic effects to all objects in the environment. Examples of FFE's are vibrations or attraction/rejection fields surrounding objects. The audio editor allows the attachment of three types of auditory feedback to the objects: (a) labels (e.g., "a bird chirp" represented the windows), (b) explicit names (e.g., "first door" or "second box"), and (c) a "guiding agent" which reports on features of the objects (e.g., the proximity of corners) or required turns (e.g., "turn left").

In the learning mode, the users navigate the environment by means of the Force Feedback Joystick (FFJ). During the navigation in the MVE the user faces forward and is allowed to move to the right, left, backward, or diagonally (always facing forward). While "walking" the participants interact with the virtual spatial components. They perceive the shape, dimensions, and relative location of objects, or they identify the structural configuration of the room (e.g., presence and location of walls, doors, or windows). As part of these interactions the users get haptic-feedback through the FFJ and audio feedback as well.

Fig. 1 shows the user-interface screen. The circles around each object indicate the hot spots that trigger the guiding agent's intervention when reached.

Several additional features are offered to the teachers during and after the learning session. Monitoring frames, for example, present updated information on the user's

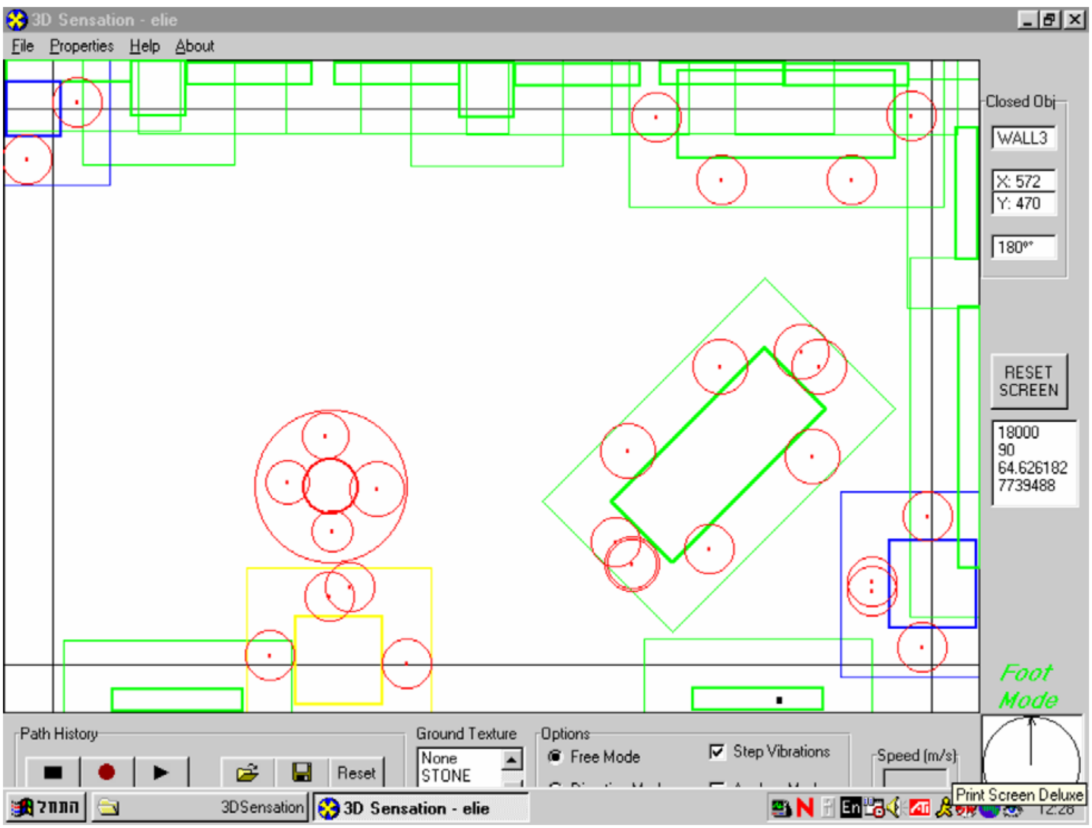

Fig. 1. The user's interface.

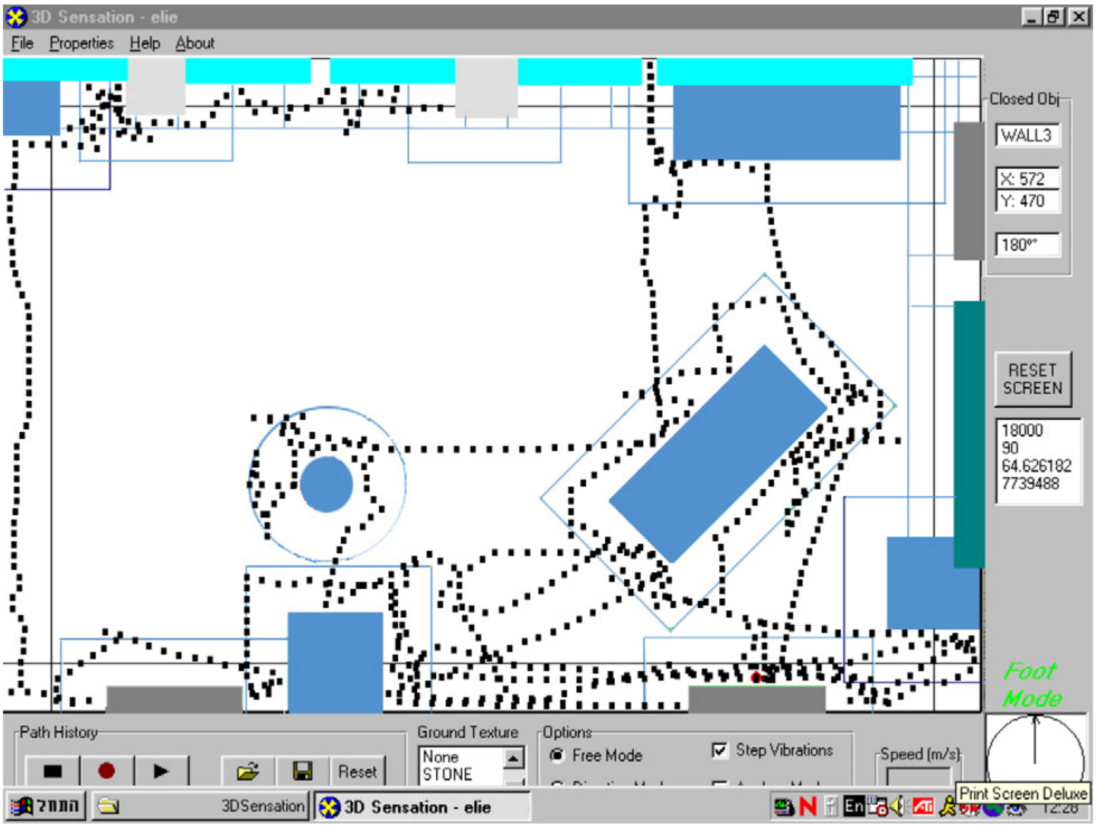

Fig. 2. Recorded log and monitoring data.

navigation performance (e.g., participant's position or objects already reached). Another feature records the participant's navigation path and can be replayed for purposes of analysis and evaluation (Fig. 2).

3. Methodology

The results reported here are part of a larger research project that examined the contribution to people who are blind when working with an MVE to develop a cognitive map for anticipatory mapping of unknown spaces and the application of the cognitive map for the actual navigation in real spaces. As indicated in the research questions, in this paper we focus on the experimental and control groups' cognitive mapping of the unknown space while navigating in either only the MVE or in correspondence with the real space (a detailed description of other segments of the research project appear in Lahav, 2003; Lahav & Mioduser, 2003, 2004).

3.1. Participants

The study included 31 participants who were selected on the basis of seven criteria: total blindness, age (at least 12 years old), not multi-handicapped, trained in O&M, Hebrew speakers, onset of blindness at least 2 years prior to the experimental period, and comfortable with the use of computers. The participants ranged in age from 12 to 70 years old.

We defined two groups that were similar in gender, age, and age of vision loss (congenitally blind or late-blind). The experimental group included 21 participants who explored the unknown space by means of the MVE. 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 ability among participants in both groups.

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

Regarding the research population we should clarify here a methodological constraint. The target population for this research was Israeli people who are blind, selected by the seven criteria above mentioned (this was substantial for pursuing appropriate data collection according to the research questions), and who agreed to participate in the study. As a result, 31 subjects participated, of which 21 were assigned to the experimental group in correspondence with the requirements of the defined variables, and the remaining 10 to the control group.

3.2. Variables

The independent variable in this study is the type of environment explored by the participants: the MVE and the real space (represented in the MVE).

The study's dependent variables relate to the participants' cognitive map of the explored space. The target space was a 54-m^2 room with three doors, six windows, and two columns, and it included seven objects (Fig. 3). Fourteen dependent variables were defined in three groups: (a) cognitive map structural components, (b) spatial relationships estimation, and (c) cognitive map construction process.

Eight variables related to the *cognitive map structural components* referred to the accurate mapping of: (1) room size, (2) room shape, (3) structural components (e.g., doors, windows), (4) structural component location, (5) objects within the room (e.g., boxes, cubes), (6) object location, (7) object size, and (8) object position.

Three variables were related to *spatial relationships estimation*: (1) references creation (e.g., landmarks, spatial relations – behind, nearby), (2) directions estimation (e.g., to the north, room's center), and (3) distances estimation (e.g., close-to, steps).

Three more variables were related to the *cognitive map construction process*:

(1) *Spatial strategy* used for describing the space (e.g., "perimeter" – describing the boundaries of the room, "object-to-object" – from one object to another, "items-list" of the environment's features, or "entrance-door-perspective" descriptions).

Table 1
The study participants

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

Fig. 3. The real (simulated) environment.

(2) *Spatial model* used for describing the space (e.g., "route model" by which the environment is described in terms of as a series of displacements in space – e.g., "*go forward to the box and then turn right*", "map model" or holistic overall description of the space – e.g., "*the room is in front of the hall*", integrated representation of route and map models).
(3) *Chronology* of the descriptive process (e.g., first components described).

3.3. Research tasks

The main tasks used in the study were:

The unknown space: The control group explored the actual physical space and the experimental group explored the space as represented in the MVE (Figs. 3 and 4).

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

Data collection instruments: A set of three instruments was developed for the collection of quantitative and qualitative data:

(1) *Observations* that were video-recorded and combined with accurate computer recording of the exploration process.
(2) *Open interview* in which the participants were asked after the exploration task to describe the space verbally.
(3) *Modeling kit* 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-made objects,

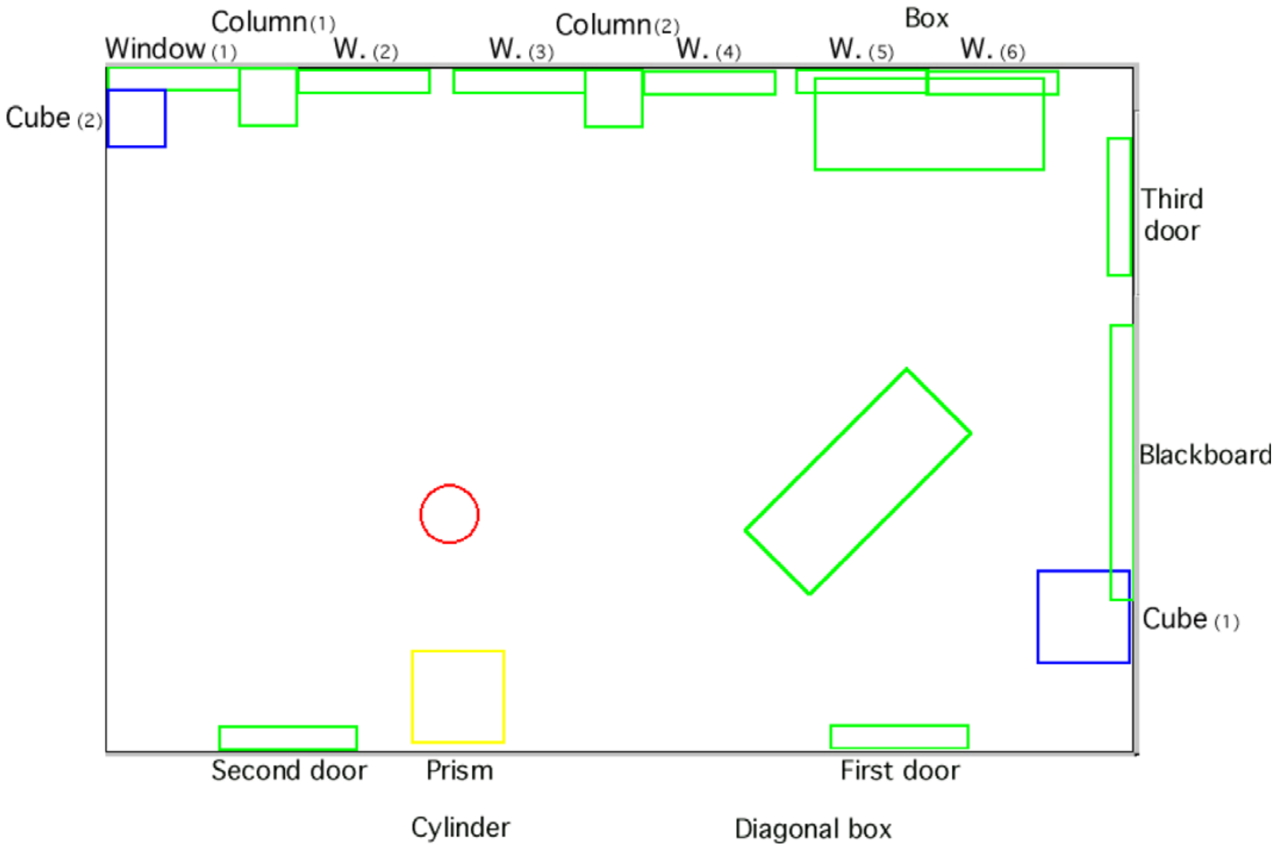

Fig. 4. The virtual environment.

five corresponding to the ones actually in the research environment (blackboard, cube, box, cylinder, prism) and three distracting objects (pyramid and special types of boxes). The room objects in the kit were provided in three different sizes (50%, 100%, and 200%) in relation to their original scale-size (see Fig. 5). 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 Kitchin and Jacobson (1997), and Passini and Proulx (1988).

The participant's verbal description was transcribed and the models were digitally photographed. An evaluation and coding scheme was developed for analyzing both the verbal description and the physical models. The evaluation and coding scheme used to analyze the verbal description and physical models was based on the above described 14 dependent variables, defined in three groups: (a) cognitive map structural components, (b) spatial relationships estimation, and (c) cognitive map construction process.

Data analysis comprised descriptive and statistical analyses. Due to the size of the population and the type of analyses conducted, it was not appropriate to perform statistical correction on the unequal number of participants in the experimental and control groups.

3.4. Procedure

All participants worked and were observed individually. The study was carried out in several stages. First, because none of the research participants had experience in interacting

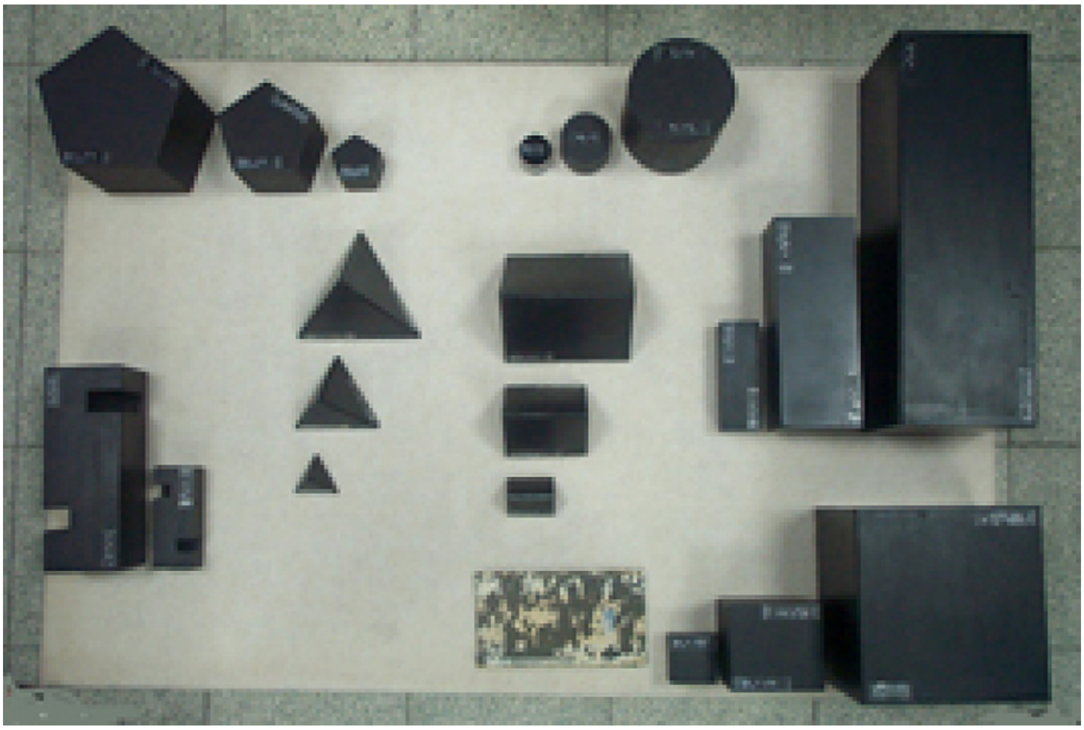

Fig. 5. The model-building kit components.

with the MVE, a short training period was needed to introduce the virtual environment and how to interact with it. During this session the participants were trained on how to operate the system (how to hold the FFJ, how to operate the help keys), introduced to the virtual environment's components, trained how to "walk" in it, and introduced to the force feedback effect and auditory feedback features. The training did not include any learning or training about O&M strategies. 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 verbal description of the space and to construct a scale physical model of it using the modeling kit. This stage lasted about 1.5–2.5 h and was video-recorded.

4. Results

Research Question 1: What *structural components and relationships* are included in the cognitive maps generated by people who are blind who explored the space in either virtual or real modes?

The data sources for this question were the participants' verbal descriptions and physical models. The examination of the descriptions and models focused first on the room's structural features: room size, room shape, structure components, and their location. The results are presented in Table 2. Note, dashes in Tables 2–4 and Table 6 indicate that the subjects were not mentioned this component in their verbal description or model. More control group participants produced an accurate verbal description about the room's size ($\chi^2(2) = 9.07$, $p < 0.05$) and the room's shape ($\chi^2(2) = 7.02$, $p < 0.05$) than the participants in the experimental group. The participants in the experimental group performed better than the ones in the control group in describing the structures' components

Table 2
Participants' descriptions of room's features

	Experimental group ($N = 21$)	Control group ($N = 10$)	
Verbal description			
Rooms' size description*	–	5 50%	(From number of participants)
Rooms' shape description*	3 15%	6 60%	(From number of participants)
Structure's components description**	46%	16%	(From number of components)
Structure's components location**	20%	7%	(From number of components)
Model configuration selection	20 95%	10 100%	(From number of participants)

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

($t(28) = 4.63$, $p < 0.001$) and their location ($t(29) = 2.85$, $p < 0.001$). During the construction of the physical model, most of the participants selected the right model among three options – 95% in the experimental group and 100% in the control group.

A detailed examination of the verbal descriptions (Table 3) shows that those generated by participants in the experimental group were more elaborated and specific about particular components (e.g., "the first door – entrance-door" or they specifically referred to windows and pillars) than those produced by the control group. The case of the first door, which served as entrance-door for most tasks performed by the participants, is of particular interest. We can assume that participants in both groups were well aware of it. However, while most in the experimental group included it as integral component of the room, only two in the control group did so.

The data collected about the objects located in the inner space relate to four variables: objects mentioned, estimation of objects location, estimation of objects size, and objects placement in the room. The values for these variables in both the verbal description (VD) and construction of the physical model are shown in Table 4. A significant difference between the groups was found in the means for the overall reference to the objects in the verbal description ($t(29) = 0.15$, $p < 0.05$) and in the models constructed ($t(29) = 4.13$, $p < 0.05$). The description from the participants in the experimental group was more specific and elaborate than the descriptions from the participants in the control group. For example, in both the verbal description and the model, most participants in the experimental group included information about the diagonal box and prism (91% and 100% in correspondence), in contrast with the control group (60% and 70%); the blackboard was mentioned by 62% (verbal description) and 67% (model) by the participants in the experimental group, in contrast with 20% of the participants from the control group. In the physical models, 29% of the experimental group participants placed all seven objects in the environment, and 43% placed six objects, in contrast with the control group participants, of which none placed all objects in their models and only 30% placed six.

Table 3
Participants' description of structure's components

	Experimental group ($N = 21$)	Control group ($N = 10$)
Doors	–	2 20%
First door	15 71%	2 20%
Second door	9 43%	4 40%
Third door	5 24%	3 30%
Windows	7 33%	5 50%
First window	7 33%	–
Second window	3 14%	–
Third window	7 33%	–
Fourth window	6 29%	–
Fifth window	5 24%	–
Sixth window	4 19%	–
Pillars	3 14%	–
First pillar	10 48%	–
Second pillar	10 48%	–

It should be noted that the participants were not limited in time for accomplishing the exploration task. Concerning the duration of the exploration, 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 an average distance of three times more ($M = 256$ m) than the control group participants ($M = 96$ m). The participants in the experimental group switched their strategies frequently during their walk in the MVE, in contrast with the participants in the control group who walked in the real space. This behavior is reflected in the total and average frequency of use of the various strategies by both groups, total frequency of 297 ($M = 14$) for the experimental group and total frequency of 65 ($M = 6.5$) for the

Table 4
Mention of room components (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

control group. The participants used this time for memorizing spatial information, reflecting on a recently implemented exploration strategy, or planning their upcoming exploration in the MVE. A significant difference was found between the groups ($t(26) = 7.65$, $p < 0.001$; $t(25) = 2.56$, $p < 0.05$) for pauses (more than 10 s). The experimental group made pauses about three times more often.

As a result of scanning the room multiple times in many directions and from different perspectives, the participants were able to perceive it as a complex whole comprising both structural and inner components. In contrast, the real space explorers referred mainly to the inner space of the room, looking at it inwardly and focusing mainly on what they perceived as relevant parts and features encountered during their navigation.

Three aspects of the participants' perception and mapping of relationships among spatial components were examined: the creation of spatial references, estimation of direction-towards-other-objects, and estimation of distances. The participants included expressions or gestures indicative of their ability regarding these aspects in their verbal descriptions and models (see Table 5).

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

Table 5
The mean number of expressions on spatial relationships in the verbal descriptions and models

	Experimental group ($N = 21$)	Control group ($N = 10$)
Creating spatial references		
VD*	4.7	1.6
Model	3.9	2.8
Estimating direction		
VD	4.6	4.1
Model	0.09	0.30
Estimating distances		
VD	2.3	0.9
Model	0.52	0.50

* $p < 0.05$.

(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.

Research Question 2: What are the characteristics of the *cognitive mapping process* by people who are blind who explored the space in either virtual or real modes?

Three interesting aspects about the cognitive map construction process were reflected in the participants' verbal descriptions: spatial description templates, spatial description strategies, and referential objects initially mentioned in the descriptions.

The participants used four types of spatial description templates to describe the environment (Table 6): *perimeter description* (e.g., N., a 33-year-old late-blind male, from the experimental group, described the environment: *on one of the walls there is the first door, the prism, another door…the prism between them…continue with this wall and you can reach the cube, blackboard, door…*); *object-to-object description* (e.g., G., a 12-year-old congenitally blind female from the experimental group, said: *at the lower wall there are two doors and near to one of them there is a cube and near the other one there is a prism…*); *items-list* (e.g., V., a 17-year-old congenitally blind female from the experimental group said: *I found prism, door and there is also a pillar, a diagonal box and a square*); and description from the *entrance-door point of view* (e.g., M., a 39-year-old late-blind female from the experimental group said: *if you walk to the left of the door, when the door is behind you can reach the prism…walking forward you can find five or six windows at the wall in front of the door…*).

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 were actively involved, a process that is subjectively enacted rather than objectively described.

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

Table 6
Cognitive mapping processes as reflected in the verbal descriptions

	Experimental group ($N = 21$)	Control group ($N = 10$)
Spatial description		
Perimeter description	8 38%	2 20%
Object-to-object description	7 33%	2 20%
Item-list description	4 19%	4 40%
Entrance-door point of view	2 10%	1 10%
Other	–	1 10%
Spatial strategy		
Route model	8 38%	3 30%
Map model	7 33%	5 50%
Integrated representation	6 29%	2 20%

group, the map model strategy was predominant. Again, an indication of the differential character of the processes (procedural or declarative) elicited by the spatial exploration in either virtual or real mode.

Examining the sequence of items mentioned in the verbal descriptions, 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.

5. Discussion

The findings of the present study provide stronger evidence that the participants' work within the MVE supported the appropriate cognitive mapping of the unknown space. In this section, we will briefly elaborate on the implications of these findings.

Regarding our first research question on the structure and quality of the participants' cognitive maps, we found that the maps done by the MVE participants were overall more holistic and comprehensive than those of the control group (as reflected in their verbal descriptions and physical models). This can be attributed to the particular exploration and map construction strategies afforded by the MVE's features. The MVE allows the participant to navigate the space freely starting from any possible location and to scan it in all possible directions for as long as the person considers necessary. During the navigation, multi-sensory feedback is continuously provided in different forms and channels about the identity, location, and position of each object in the environment.

In contrast, the exploration process in real spaces by people who are blind is essentially linear. The scanning space at each stage is limited by the reach of the arm or the length of the cane. Even aid supplied by other technologies (e.g., tactile maps, verbal descriptions by sighted people, and personal guidance system) is usually in one sensorial modality at a time and lacks fine resolution information. The unavoidable trade-off between these technologies is extent and resolution. For example, scaled tactile maps allow the complete scanning of a space, but typically at a very low-resolution. The MVE resolves this compromise by allowing both the overall scanning of the space as well as the collection of specific and detailed information about its features and components. With this unique feature, the participant chooses her or his level of scanning of the space at any given stage of the exploration depending on specific needs during the mapping process. Comprehensive exploration of the unknown space in the MVE required time. Similar results have been reported in previous studies. Darken and Peterson (2002), and Waller et al. (1998) compared sighted participants' exploration of spaces by means of MVE, other information-technology spatial devices, and directly in the real space, and they found that exploration in the MVE required the longest amount of time. However, they also found that the longer duration of exploration in the MVE affected the participants' performance in the real space: they performed better than participants exposed to other spatial exploration devices. Similar results are presented in our research. The longer duration of the exploration in the MVE enhanced the participants' ability to construct a cognitive map. Nevertheless, the quality of the exploration process is based on the length of the exploration path, strategies that were used, and the pauses that were used for memorizing and reflecting on spatial information during a walk in the MVE. It is reasonable to expect that exploration-time will become shorter as participants become accustomed to using MVE systems as learning tools. This study's results show clearly how this feature affected the quality and composition of the cognitive maps constructed by the experimental group participants: their maps were holistic depictions of the explored space (including allusion to its outer envelope less considered by the control group participants), together with highly accurate and detailed references to specific structural and inner components.

Regarding our second research question on the characteristics of the mapping process, a central finding of our study relates to the modality of this process: mainly procedural by the experimental group participants and mainly declarative by the control group participants. These modalities were clearly reflected in the description strategies and templates and the temporal configuration characterizing the participants' verbal descriptions and model-building. Participants in the experimental group recalled the space's features integrating between *what* is in the room and *how* this information was gathered, using process-like retrieval strategies. They also followed a description pattern that goes from the structure inwards (in contrast with the control groups' pattern going from inner spatial components outwards). This can be seen again as indicative of the participants' multi-layered perception of the new space.

Previous research found that the visual deficit in navigational capability is that many people who are blind become passive, depending on others for continuous aid (Foulke, 1971). More than 30% of the blind do not ambulate independently outdoors (Clark-Carter, Heyes, & Howarth, 1986). In light of the encouraging results of this study, we can conclude that the work within the MVE provided a strong foundation for the participants' development of comprehensive cognitive maps of the unknown space. The results of this study expressed the possible contributions of the MVE to their O&M abilities from different aspects: O&M rehabilitation trainee, the construction of spatial cognitive map, and consequently to blind people's spatial independent performance. Further research is needed to advance even more understanding of cognitive mapping of spaces for people who are blind about a broad scope of additional issues. These additional issues might include the effect of virtual tools that support the estimation of distances, scale, relative dimensions, etc. on the quality of the generated maps; the effect of explicit training on virtual-exploration strategies on actual exploration-time of new spaces, people's ability to explore and map spaces of varied nature (e.g., open spaces, public buildings, workplaces), or the effect of time on long-term retrieval of cognitive maps of spaces generated within MVEs. Research knowledge on these and other issues may lead to successful implementation of MVEs as powerful O&M tools for supporting people who are blind outside of the research environment.

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