Blind persons' acquisition of spatial cognitive mapping and orientation skills supported by virtual environment

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Abstract: Mental mapping of spaces, and of the possible paths for navigating these 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. Blind people lack this crucial information and in consequence face great difficulties (a) in generating efficient mental maps of spaces, and therefore (b) in navigating efficiently within these spaces. The work reported in this paper follows the assumption that the supply of appropriate spatial information through compensatory sensorial channels, as an alternative to the (impaired) visual channel, may contribute to the mental mapping of spaces and consequently, to blind people's spatial performance. The main tool in the study was a virtual environment enabling blind people to learn about real life spaces, which they are required to navigate.

Keywords: Visual impairment; Mobility; Visual impairment through virtual simulation; Rehabilitation; Cognition; Cognitive processing and virtual environments; Haptic devices; Training tools for rehabilitation

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INTRODUCTION

The ability to explore unknown spaces independently, safely and efficiently is a combined product of motor, sensory and cognitive skills. Normal exercise of this ability directly affects individuals' quality of life. 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 (1). People who are blind lack this information, and in consequence they are required to use compensatory sensorial channels and alternative exploration methods (2). 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 (3).

Research on O&M skills of people who are blind in known and unknown spaces (4, 5) 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 by information perceived via other senses. The haptic, audio and smell channels become powerful information suppliers about unknown environments. For blind individuals, haptic information is commonly supplied by the white cane for low-resolution scanning of the immediate surroundings, by palms and fingers for fine recognition of object form, texture and location, and by the feet regarding navigational 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 (6).

As for 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. Research indicates that people use two main scanning strategies: route and map strategies. Route strategies are based on linear (and therefore sequential) recognition of spatial features, while map strategies, considered to be more efficient than the former, are holistic in nature, comprising multiple perspectives of the target space (7, 8). Research shows that people who are blind use mainly route strategies when recognizing and navigating new spaces (7).

Advanced computer technology offers new possibilities for supporting rehabilitation and learning environments for people with disabilities (e.g., sensorial, physical, mental, and learning disabilities) (9). It has also been used for rehabilitation for blind people; in particular, Virtual Environment (VE), which includes haptic interface technology, enables blind individuals to expand their knowledge as a result of using artificially made reality through haptic and audio feedback. Research on the implementation of haptic technologies within virtual navigation environments has yielded reports on its potential for supporting rehabilitation training with sighted people (10, 11), as well as with people who are blind (12, 13). Related research on the use of haptic devices by people who are blind, includes the following: identification of texture and object shape (14), mathematical learning environment and exploring of mathematical graphs (15), and construction of cognitive maps (16, 17). In our previous research, we have shown that the use of VE technology helped people who are blind in exploring an unknown novel room (18, 19).

The research reported in this paper follows the assumption that the supply (via the technology) of compensatory perceptual and conceptual information may contribute to blind persons' cognitive mapping of spaces. To examine the above assumption we developed a multimodal-virtual-learning-environment (MVLE) and studied the exploration process of an unknown space by blind subjects using this VE. Their performance was compared to that of a control group of blind people who explored directly the real environment simulated in the MVLE. The main research questions of this study were:

1. What characterizes a blind person's exploration process of an unknown environment using a VE?
2. Does walking in the VE contribute to the construction of a cognitive map of the unknown space?
3. How does this cognitive map contribute to the blind person's O&M performance in the real environment?

THE HAPTIC VIRTUAL ENVIRONMENT

For the study we developed a VE simulating real-life spaces. This VE comprises two modes of operation:

Developer/Teacher Mode

The core component of the developer mode is the VE editor (Figure 1). This module includes three tools:

- 3D environment builder – using this builder the developer defines such physical characteristics of the space as size and form of the room, type and the size of objects (e.g., doors, windows, furniture pieces) and their location. Although the environment builder is based on a 3D editor, for this research we used a 2D environment only.

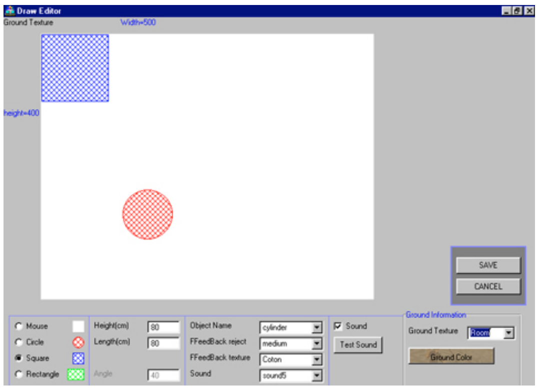

Figure 1. *3D environment editor.*

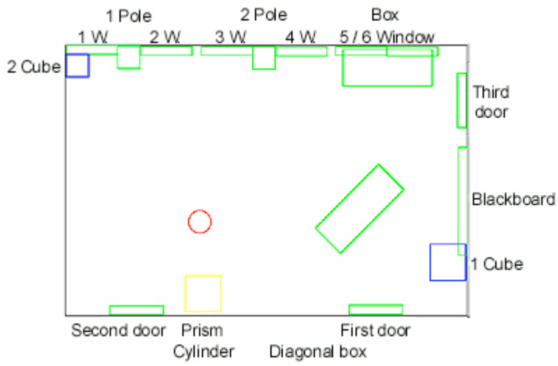

Figure 2. *The VE representation of the target space.*

- Haptic feedback output editor – this editor permits the developer to attach force-feedback effect to all components in the VE. The main haptic feedback is the kinesthetic force that the user feels through the Force Feedback Joystick (FFJ). The user feels the variation in texture and friction of the virtual component simulated in the VE.

- Audio feedback output editor – the audio feedback was used to provide the user with a comfortable channel carrying descriptive information. Our VE includes three types of audio feedback: (i) the intentional tapping or accidental bump with the force feedback joystick on one of environments' components (e.g., doors, walls, or box) initiates the audio feedback indicating the object's identity; (ii) the computer automatically generates an audible alert when approaching obstacles' corner; (iii) during navigation, the provision of footstep sounds and echoes increases not only the reality to the blind user, but also the sense of actual scale. The sound interval of the footsteps shows the speed of the navigation; and the user's stride-length is the benchmark for distance in the virtual scene.

Learning Mode

The learning mode, within which the user works, includes two interfaces:

- User interface – the user interface consists of the VE that simulates real rooms and objects to be navigated by the users using the FFJ (Figure 2).

- Teacher interface – the teacher interface includes several features that serve teachers during and after the learning session. On-screen monitors present updated information on the user's navigation performance, such as position, or objects already reached. An additional feature allows the teacher to record the subject's navigation path, and replay it to analyze and evaluate the user's performance (Figure 3).

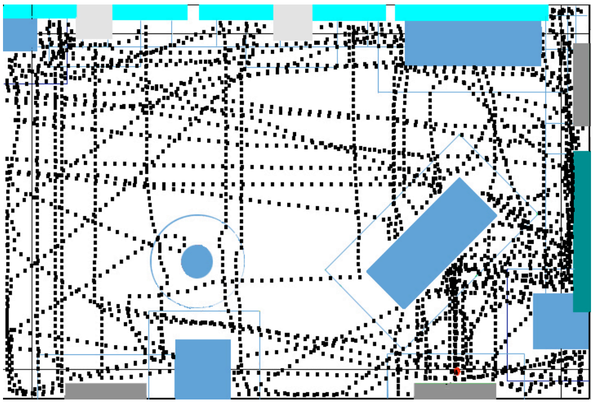

Figure 3. *Subject's navigation path.*

Figure 4. *The real space.*

METHOD

Subjects

The study included 31 subjects who were selected on the basis of the following seven criteria: (i) total blindness; (ii) at least 12 years old; (iii) not multi-handicapped; (iv) received O&M training; (v) Hebrew speakers; (vi) onset of blindness at least two years prior to the experimental period and (vii) comfortable with the use of computers. The subjects' age range was 12-70 years, mostly adults in the age range of 24-40. We defined two groups that were similar in gender, age and age of vision loss (congenitally blind or late blind): The experimental group, including 21 subjects who explored the unknown space by means of the VE, and the control group, including ten subjects who explored directly the real unknown space.

Research Instruments

Seven main instruments served the study; the last five instruments were developed for the collection of quantitative and qualitative data. The research instruments were:

- The Unknown Target Space – The space to be explored, both as real physical space (see Figure 4) and as a virtual space in the VE (see Figure 2), 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.

- Exploration Task – Each participant was asked individually to explore the room, without time limitations. The experimenters informed the subjects that they would be asked to describe the room and its components at the end of their exploration.
- Orientation and Mobility Questionnaire – The questionnaire comprised 46 questions concerning the subjects O&M ability indoors and outdoors, in known and unknown environments. Most of the questions were taken from O&M rehabilitation evaluation instruments (20, 21).
- Interview – An open interview used for the subjects' verbal description of his exploration in the unknown environment.
- Observations – For recording the participant's exploration, we used video-recorder and notebook. Their navigation process and audio remarks in the VE and the real space were recorded during the tasks. The information from these recordings was combined with the computer log recording.
- Computer Log – The Log allowed the researchers to track the user's learning and exploration process in the MVLE, as regards to their exploration strategies, distances traversed, duration, switch of strategies and breaks.
- Evaluation and Coding Schemes – These instruments served the experts' analysis of the participant's O&M skills and capabilities and his or her acquaintance process with the new space.

Procedure

All subjects worked and were observed individually. The study was carried out in five stages: (i) evaluation of the subjects' initial O&M skills, using the O&M questionnaire; (ii) familiarization with the VE features and how to operate the FFJ (the experimental group); (iii) subjects' exploration of the unknown space: the experimental group explored the space using the VE, while the control group explored the real environment directly; (iv) following the exploration task the subjects were asked to give a verbal description of the environment, and to construct a scale model of it; (v) performing O&M tasks in the real target space: Target-object task (the user will be ask to find an object in the space); Perspective-taking task (the user will enter the room by a different entrance and asked to find an object). In the last four stages all subjects' performances were video-recorded.

RESULT

Research Question 1: *What characterizes a blind person's exploration process of an unknown environment using a VE?*

Significant differences were found between the experimental group and the control group concerning the characteristics of the exploration process. These differences are related to four variables: the total duration of the exploration, the total distance traversed, the sequence of main strategies implemented and the number of pauses made while exploring the unknown space. Data in Table 1 show significant differences between the experimental and the control groups in that the experimental group took more breaks during their exploration tasks.

Table 1. *Short and long breaks*

Group	Long breaks	Short breaks
Experimental group (n=21)	17	81
Control group (n=10)	6	13
	*	**

$p<.05$; ** $p<.001$

The subjects in both groups implemented similar exploration strategies, mostly based on the ones they use in their daily navigation in real spaces (for example: "perimeter", i.e. walking along the room's walls and exploring objects attached to the walls; "grid", i.e.. exploring the room's inner-space). However, an interesting additional finding is that several subjects in the experimental group developed a few new strategies while working within the VE. Those strategies could be generated only within the VE, representing an important added value of the work with the computer system. Although no substantial difference between groups was observed as regards the types of strategies used, significant difference was found concerning the frequency of use of the strategies, and 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. A detailed presentation of the findings of the exploration stage can be found in Lahav & Mioduser, (19).

Table 2. *Exploration strategies, frequency and length*

	Experimental group (n=21)		Control group (n=10)	
Exploration patterns	Frequency	Length of the path (In meters)	Frequency	Length of the path (In meters)
Perimeter	86	53.9	28	14.6
Grid	116	26.3	9	.97
Object-to-object	22	7.8	14	2.3
Points of reference	50	26.6	13	1.8
New strategies	18	18.2	--	--
Sum	292	132.8	64	19.67
Mean	14	6.3	6.4	1.9

Research Question 2: *Does walking in the VE contribute to the construction of a cognitive map of the unknown space?*

After completing the exploration task the subjects were asked to give a verbal description and to construct a model of the environment. Four variables of the subjects' verbal and physical representations were examined: room size, room shape, structural features and components' location. The control group subjects (who explored the real space directly) performed better in verbally describing the rooms' size ($\chi2(2)=9.07$; $p<0.05$) and the rooms' shape ($\chi2(2)=7.02$; $p<0.05$). The subjects from the experimental group performed better in describing the structural components ($t(28)=4.63$; $p<0.001$) and their location ($t(29)=2.85$; $p<0.001$).

Most subjects in both groups constructed an appropriate model of the room and its components. Data related to aspects of the subjects' reference to structural components and objects in the environment are shown in Table 3. Significant differences between the two research groups were observed in six variables. The data demonstrated that the information resolution of the components of the cognitive map built by subjects of the experimental group was finer in detail than the map built by subjects of the control group.

Table 3. *Cognitive map construction - verbal description and model construction*

	Verbal description			Model construction		
	Experimental group (n=21)	Control group (n=10)		Experimental group (n=21)	Control group (n=10)	
Room size	--	50%	*			
Room shape	15%	60%	*			
Structures' components	46	16	**			
Estimation Structures' components location	20	7	*			
Model structure				95%	100%	
Objects	79	53	*	83	48	*
Estimation object location	60	40		50	28	
Placing object in the room	2	3		60	29	
Estimating object size	0.7	10		41	27	

*$p<.05$; **$p<.001$

The experimental group's representation was more specific and elaborate, in both verbal description and model construction. For example, 29% of experimental group subjects placed all seven objects located in the environment in their model, and 43% placed six objects. In contrast, none of the control group subjects placed all seven objects in their model and only 30% placed six objects.

The findings for the second question indicate that the experimental group subjects constructed fairly complex cognitive maps of the unknown space, as reflected in their verbal and physical descriptions. These maps comprise multiple layers, including the structural layer (referring to the overall configuration and dimensions of the room), the compositional layer (in relation to the identification of inner components and their arrangement in space), and the relational layer (location of objects relative to each other, or distances among objects). A procedural component complements the previous layers in the form of strategies for exploration/recall of the target space (e.g., perimeter, object-to-object). The learning process within the VE, by its unique features, supported the construction of a knowledge-rich model at all its different layers. A detailed presentation of the findings of the cognitive map construction stage can be found in Lahav & Mioduser (20).

Research Question 3: *How does this cognitive map contribute to the blind person's O&M performance in the real environment?*

After the construction of the cognitive map, the subjects were asked to perform two orientation tasks in the real space. It should be recalled that the experimental group subjects 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: successful completion of the tasks; use of direct paths to the target location; time spent on task; number and duration of breaks (short breaks and long breaks) and total length of the path (see Table 4). Most of the subjects of the experimental group successfully performed both orientation tasks in the real space. Significant difference was found between the groups in the subjects' performance in the target-object task. Most subjects of the experimental group successfully performed the target-object task while choosing a more direct and shorter path than the control group subjects; about half of the experimental group subjects choose a straight walking path and the "Object-to-Object" strategy. When examining the perspective-taking task, most subjects of the experimental group successfully performed the task in shorter time and path length, 50% using the "perimeter" strategy.

Table 4. *Performance in the real environment*

	Target-object task			Perspective-taking task	
	Experimental group (n=21)	Control group (n=10)		Experimental group (n=21)	Control group (n=10)
Success (%)	81%	40%	*	71%	60%
Direct path (%)	67%	20%	**	34%	30%
Time (Seconds)	66	118		153	191
Short breaks (mean)	3	6		3	5
Long breaks (mean)	1.5	2.7		1.5	3
Length of the path	28	47	***	86	95

* $\chi2(2)=7.02$; $p<0.05$; ** $\chi2(3)=8.20$; $p<0.05$; *** $p<0.05$

The results are clearly indicative of the contribution of VE learning 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 greater capability of the subjects of the experimental group in performing the real-space tasks.

CONCLUSIONS

Exploration of an unknown environment using a VE

Walking in the VE gave participants a stimulating, comprehensive and thorough acquaintance with the target space. The high degree of compatibility between the components of the VE and of the real space on one hand and the exploring methods supported by the VE on the other, contributed to the users' relaxed and safe walking. These features also enabled participants to implement exploration patterns they commonly used in real spaces, but in a qualitatively different manner. The use of "real exploration strategies" in VEs was reported in previous studies on spatial performance by sighted participants (23, 24). But this study's VE 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 (2). Moreover, the VE participants created new exploration strategies, such as the one simulating walking with a long cane enabling them to walk the perimeter of the room and at the same time to explore its corresponding inner areas – a strategy only possible within the VE. Operation features of the VE (e.g., the game-like physical interface, multiple types of feedback) contributed to participants' confident performance with the system while exploring the unknown space. As a result, the exploration process showed interesting qualities concerning spatial, temporal, and thinking-related aspects. Examples of spatial and temporal qualities are the range of scanning strategies implemented, the inclusion of a large number of long and short breaks, or the time spent in examining the space. Concerning thinking-related aspects of the process, interesting examples were the long breaks made by the participants with the aim to reflect on the exploration steps or to memorize data concerning an explored area, or the use of "virtual drawing" of spatial features under examination on the table's surface as reinforcement aid.

Construction of a cognitive map of the unknown space as a result of learning with the VE

Participants in the experimental group were able to construct complex maps of the unknown space while working with the VE, prior to their acquaintance with the real space. As a result of their intensive interaction with the components of the virtual learning environment, the users were exposed to a wide range of haptic and audio feedbacks. This information allowed them to devote most of their attention and resources to the consolidation of the structural, compositional and relational aspects of the space's overall map. In addition, it seems that the participants developed particular perspectives of the space, and strategies for approaching it, as a result of the features of the VE (e.g., the tendency to describe the space from the perimeter to the inner space, in a whole and holistic manner). In contrast, we found that the exploration of the real space contributed to the control group's ability to estimate the objects' size and distances among them, functions not supported yet in the VE.

Performance of O&M tasks as a result of learning with the VE
The first real space walking experience of most subjects in the experimental group was a confident and resolved one. It was noticeable that this walking was based solely on spatial knowledge acquired as a result of their acquaintance with the room in the VE. We found many evidences of the robustness of the constructed map and its contribution to the subjects' performance. One example is their frequent use of the "Object-to- Object" strategy while accomplishing the tasks. Previous research (25, 6) reported that successful navigators among people who are blind make recurrent use of this strategy. The frequent use of this strategy by participants in the experimental group is indicative of the holistic nature of their inner representation of the space, allowing them to construct efficient navigation paths based on isolating subsets of objects and their relative location. This internal representation represents a powerful tool for guiding the secure navigation in the real space immediately after entering it, and for locating all spatial components required to perform the task in the shortest possible time and ambulation path.

Current constraints and future implications
In this first attempt to examine an exploration task, the cognitive mapping process, and its effect on actual performance we had to stay within the limits of the first stage of a more comprehensive research agenda. For example, in selecting the characteristics of the target space in this first stage we focused on a closed space without complicated topographical traits (which represent a complete set of additional variables that might lead to different results). Based on this first stage our research agenda includes the modeling of increasingly open and complex spaces (e.g. university campus, museum, public building), the offering of additional exploration tools, and the study of overall exploration and mapping strategies by people who are blind who recurrently use the VE for different spaces. We believe these studies are of theoretical and practical value for (a) training and rehabilitation processes requiring the acquisition of orientation and mobility skills and strategies, and (b) learning processes of subjects involving spatial information, by congenital and late blind people.

ACKNOWLEDGEMENTS

This study was partially supported by grants from the Israeli Ministry of Education, Microsoft Research Ltd., and Israel Foundation Trustees.

REFERENCES

1. Lynch, K. (1960). *The image of the city*. Cambridge, MA: MIT Press.
2. Jacobson, W. H. (1993). *The art and science of teaching orientation and mobility to persons with visual impairments*. New York, NY: American Foundation for the Blind.
3. Mioduser, D. (2005). From real virtuality in Lascaux to virtual reality today: Cognitive processes with cognitive technologies. In T. Trabasso, J. Sabatini, D. Massaro, & Robert C. Calfee (Eds). *From orthography to pedagogy: Essays in honor of Richard L. Venezky* (pp. 173-192). Mahwah, NJ: Erlbaum.
4. Passini, R., & Proulx, G. (1988). Wayfinding without vision: An experiment with congenitally blind people. *Environment and Behavior, 20*, 227-252.
5. Ungar, S., Blades, M., & Spencer, S. (1996). The construction of cognitive maps by children with visual impairments. In J. Portugali (Ed.), *The construction of cognitive maps* (pp.247-273), The Netherlands: Kluwer.
6. Hill, E., Rieser, J., Hill, M., Hill, M., Halpin, J., & Halpin R. (1993). How persons with visual impairments explore novel spaces: Strategies of good and poor performers. *Journal of Visual Impairment and Blindness*, 295-301.
7. Fletcher, J.F. (1980). Spatial representation in blind children 1: development compared to sighted children. *Journal of Visual Impairment and Blindness, 74* (10), 318-385.
8. Kitchin, R.M., & Jacobson, R.D. (1997). Techniques to Collect and Analyze the Cognitive Map Knowledge of Persons with Visual Impairment or Blindness:Issues of Validity. *Journal of Visual Impairment and Blindness*, 91 (4), 360-376.
9. Schultheis, M. T., & Rizzo, A. A. (2001). The application of virtual reality technology for rehabilitation. *Rehabilitation Psychology, 46*(3), 296-311.
10. Giess, C., Evers, H., & Meinzer, H.P. (1998). *Haptic volume rendering in different scenarios of surgical planning*. Paper presented at the Third Phantom Users Group Workshop, M.I.T. Cambridge, MA.
11. Gorman, P.J., Lieser, J.D., Murray, W.B., Haluck, R.S., & Krummel, T.M. (1998). *Assessment and validation of force*

feedback virtual reality based surgical simulator. Paper presented at the Third Phantom Users Group Workshop, M.I.T. Cambridge, MA.

12. Jansson, G., Fanger, J., Konig, H., & Billberger, K. (1998). Visually impaired persons' use of the PHANToM for information about texture and 3D form of virtual objects. In J. K. Salisbury & M. A. Srinivasan (Ed.) *Proceedings of the Third PHANToM Users Group Workshop*, MIT, Cambridge, MA.
13. Colwell, C., Petrie, H., & Kornbrot, D. (1998). *Haptic virtual reality for blind computer users*. Paper presented at the Assets '98 Conference, Los Angeles, CA. Available in: http://phoenix.herts.ac.uk/sdru/pubs/VE/colwell.html
14. Sjotrom, C., & Rassmus-Grohn, K. (1999). The sense of touch provides new computer interaction techniques for disabled people. *Technology & Disability, 10* (1), 45-52.
15. Karshmer, A.I., & Bledsoe, C. (2002). *Access to mathematics by blind students - introduction to the special thematic session*. Paper presented at the International Conference on Computers Helping People with Special Needs (ICCHP), Linz, Austria.
16. Lahav, O., & Mioduser, D. (2000). *Multi-Sensory Virtual Environment for Supporting Blind Persons' Acquisition of Spatial Cognitive Mapping, Orientation, and Mobility Skills*. Paper presented at the 3rd International Conference on Disability, Virtual Reality and Associated Technology, Alghero, Sardinia, Italy.
17. Semwal, S. K., & Evans-Kamp, D.L. (2000). *Virtual environments for visually impaired*. Paper presented at the 2nd International Conference on Virtual worlds, Paris, France.
18. Lahav, O., & Mioduser, D. (2003). A Blind Person's Cognitive Mapping of New Spaces Using a Haptic Virtual Environment. *Journal of Research in Special Education Needs, 3* (3), 172-177.
19. Lahav, O., & Mioduser, D. (2004). Exploration of Unknown Spaces by People who are Blind, Using a Multisensory Virtual Environment (MVE). *Journal of Special Education Technology, 19*(3).
20. Dodson-Burk, B., & Hill, E.W. (1989). Preschool orientation and mobility screening. *A publication of division IX of the association for education and rehabilitation of the blind and visually impaired*.
21. Sonn, U., Tornquist, K., & Svensson, E. (1999). The ADL taxonomy - from individual categorical data to ordinal

categorical data. *Scandinavian Journal of occupational therapy, 6*, 11-20.

22. Lahav, O., & Mioduser, D. (in press). People who are Blind Construction of Cognitive Maps of Unknown Spaces using a Multisensory Virtual Environment.

23. Darken , R.P., & Peterson, B. (2002). Spatial orientation, wayfinding and representation. In K. M. Stanney (Ed.), *Handbook of virtual environments design, implementation, and applications* (pp. 493-518). Hillsdale, NJ: Erlbaum.

24. Witmer , B.G., Bailey, J. H., Knerr, B. W., & Parsons, K.C. (1996). Virtual spaces and real world places: Transfer of route knowledge. *International Journal of Human-Computer Studies, 45*, 413-428.

25. Golledge, R., Klatzky , R., & Loomis, J. (1996). Cognitive mapping and wayfinding by adults without vision. In J. Portugali (Ed.), *The construction of cognitive maps* (pp. 215-246). The Netherlands: Kluwer.