Virtual Environment Navigation with Look-Around Mode to Explore New Real Spaces by People Who Are Blind

Orly Lahav[a], Hadas Gedalevitz[a], Steven Battersby[b], David Brown[b], Lindsay Evett[b] and Patrick Merritt[b]

[a]School of Education, Tel Aviv University, Tel Aviv, Israel

[b]Computing and Technology Team, Nottingham Trent University, Nottingham, UK

Corresponding author: Orly Lahav

lahavo@post.tau.ac.il

972-3-6407981

P.O. Box 39040, Tel Aviv 69978, Israel

Keywords: Orientation and mobility; Blind; Mental map; Multimodal interaction; Virtual environment

Acknowledgments

We thank our anonymous participants for their time, effort, and ideas.

The authors report no declarations of interest

Abstract

Background. This paper examines the ability of people who are blind to construct a mental map and perform orientation tasks in real space by using Nintendo Wii technologies to explore virtual environments. The participant explores new spaces through haptic and auditory feedback triggered by pointing or walking in the virtual environments and later constructs a mental map, which can be used to navigate in real space.

Methods. The study included 10 participants who were congenitally or adventitiously blind, divided into experimental and control groups. The research was implemented by using virtual environments exploration and orientation tasks in real spaces, using both qualitative and quantitative methods in its methodology.

Results. The results show that the mode of exploration afforded to the experimental group is radically new in orientation and mobility training; as a result 60% of the experimental participants constructed mental maps that were based on map model, compared to only 30% of the control group participants.

Conclusion. Using technology that enabled them to explore and to collect spatial information in a way that does not exist in real space influenced the ability of the experimental group to construct a mental map based on the map model.

Introduction

Most of the information required for constructing a spatial mental map is based on visual information [1]. People who are blind do not have access to this crucial information and thus face great difficulties in generating efficient mental maps. Space plays an important role in everyday life. We live in it and move through it, yet we find it extraordinarily difficult to learn about it [2], especially in unfamiliar locales. The visual sense plays a primary role in guiding a sighted person through an unfamiliar space and assisting him or her to reach a destination safely. Unfortunately, people who are blind face enhanced difficulties when performing such a task. The lack of the sense of vision makes it difficult to identify locations and obstacles, or simply to find a path. A result of this deficit in navigational capability is that many people who are blind become dependent on others for continuous aid [3]. More than 30% of people who are blind do not travel independently outdoors [4]. In consequence, people who are blind are required to use compensatory sensorial channels and alternative exploration methods [5].

Research on orientation and mobility (O&M) in known and unknown spaces by people who are blind [6, 7] 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, such as touch, audio, and olfactory, people who are blind can collect information about their immediate environment and use it to orient themselves in space [7]. The auditory channel supplies essential information about events, or the presence of other people (or machines or animals) in the environment. In indoor spaces people who are blind can use echo feedback (by whistling, clapping hands, or talking) to estimate distances [8]. The smell channel supplies additional information about particular situations (e.g. perfumery, bookstore or bakery in a shopping center) or about people. Tactile information appears to be of great potential for supporting appropriate spatial performance. For people who are blind, tactile or haptic information is commonly supplied by the long cane for low-resolution scanning of the immediate surroundings, by palms and fingers for fine recognition of objects form, texture, and location, and by the feet regarding surface information.

At the conceptual level, the focus is on supporting the development of appropriate strategies for the efficient exploration of the space and the generation of efficient navigation paths. For example, Jacobson [5], described the indoor environment familiarisation process used 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.

Knowing solely the location of a particular spatial component is not sufficient for getting to, or around, the particular space, or for avoiding obstacles within this space. This spatial knowledge is beneficial only if combined with general knowledge about spaces. General knowledge can be acquired through experience in the space or through a bird's eye view of the space [9]. In both cases the representation is stored in the brain as a mental map – an external image-like representation that includes knowledge about a space, as well as knowledge of spatial relationships within that space [10].

Over the years, secondary O&M aids have been developed to help people who are blind to explore a real space (RS). These secondary aids are not a replacement for primary aids such as the long cane and the guide dog. We can divide these aids into two groups: (1) preplanning aids that provide the user with information before arrival in a space, for example, verbal descriptions, tactile maps, physical models, digital audio, and tactile screens; and (2) in-situ aids that provide the user with spatial information while in the space, for example, obstacle detectors, tactile vision substitution system [11], embedded sensors in the environment, and Global Positioning Systems. The major limitation of in-situ aids is that the user must gather spatial information in the explored space, making it impossible to build a mental map in advance, thus causing a feeling of insecurity and dependence upon arrival in a new space [12]. From the perspective of safety and isolation, in-situ aids are based mostly on auditory feedback, which in an RS can reduce users' attention and isolate them from the surrounding space, especially from auditory information [13]. Moreover, the limited dimensions of tactile maps and models may result in poor resolution of the provided spatial information. There are difficulties in publishing and acquiring updated spatial information, and they are rarely available. As a result of these limitations, people who are blind are less likely to use in-situ or preplanning aids in everyday life.

The use of virtual reality in domains such as simulation-based training, gaming, and entertainment industries has been on the rise in many fields, such as the military, education, and medicine [14]. This technology assists people with special needs in learning and rehabilitation [15]. For people with special needs, interaction in a virtual environment (VE) presents both benefits and limitations. The benefits include the user's independent interaction and activity within the VE. The VE allows the user to receive immediate feedback, encourages self-directed activity, and can provide a safe setting in which to practice skills that might carry too many risks in the real world. Initial concerns that skills or habits learned in the VE would not transfer to the RS have not been supported by the available evidence. Applications fall into three categories: promoting skills for independent living, enhancing cognitive performance, and improving social skills [16]. In addition, VE technology allows educational and rehabilitation professionals to manage the amount of information and sensorial stimuli that users receive during their interaction within the VE. These unique capabilities of VE technology-based systems justify the design and development of an adaptive learning or rehabilitation system for each client according to his or her special needs and abilities. Moreover, VE technology can assist educational and rehabilitation professionals in gathering information about their clients' interactions. VE technology also has limitations.

The VE is not a replica or replacement for RS interactions and activities. Furthermore, the expense of such systems can be a barrier to use in rehabilitation centres and schools. Additionally, some systems under development are still too heavy, bulky, or complicated for use outside the laboratory environment.

Technologically advanced virtual devices enable people who are blind to learn by using haptic and audio feedback to detect artificial representations of reality. The haptic devices transmit feeling through direct contact with the virtual object (e.g., SensAble Phantom Desktop, Immersion Corp.'s CyberForce, Novint Falacon, and Nintendo's Wii Controller). Stemming from the development of these devices, applications have been researched and developed especially for people who are blind, including identification of texture and shape recognition [17, 18] and mathematical learning environments [19-22].

Two broad groups of VEs have been designed for O&M training based on haptic and/or auditory feedback. The first group of systems supports the acquisition of a mental map [23, 12, 24 , 25-31]. The second group of systems comprises those that are used as O&M rehabilitation aids [15, 22, 32, 33]. Research findings from both groups of systems have shown that by exploring VEs that represent unfamiliar RSs, people who are blind can construct a mental map and apply this spatial knowledge successfully in familiar and unfamiliar RSs.

In a mental map the objects are encoded as either absolute or as relative to a space, and the spatial representation is represented as a route model or as a map model. A route model is based on linear recognition of spatial features, while a map strategy is holistic and encompasses multiple perspectives of the target space [34]. Research on spatial models has shown that people who are blind mainly use a route model when exploring and navigating spaces [35, 36]. The process for collecting spatial information via the above secondary O&M aids has an effect on the information coded and later affects the decision-making processes that result in spatial behavior within an environment [37]. The need to use map model arises mainly when the path is inoperative (road construction, flood, or other) and there is a need to walk along an alternative path. Simonnet [30] demonstrates that further research is needed to examine if and how the VE's spatial exploration method (allocentric or geocentric representations) influences the user's spatial representation (route model or map model). Related research (mentioned above) concerning the exploration of VEs by people who are blind has shown how users are able to 'walk virtually' in a VE to gather spatial information. Research that examines the construction of mental maps reports that people who are blind tend to use a route model [12, 24].

This paper will address two issues. First, it will explore the look-around mode of the virtual cane, which allows users who are blind to explore new spaces in a way radically different than that available in the real world. Second, it will study the influence of the look-around mode on the construction of mental maps. The main goal of this research is to understand the use of exploration strategies and their influences on the construction of mental maps and application of the mental map in the RS. For people who are blind, this special look-around mode is made possible only by the virtual cane technology. This study includes three main research questions:

1. What exploration strategies and processes do people who are blind use when working with the VE Wii-based system in the experimental and the RS in the control groups?
2. What were the participants' mental mapping characteristics in the experimental and control groups?
3. How did both research groups perform orientation tasks in the RSs?

The virtual cane: system overview

In this research we used the Nintendo Wii Controller (Wiimote) as a preplanning aid for exploring VEs that represent RSs (Figure 1). This technology has many advantages; it is widespread, cheap, popular, and easy to use with a standard PC [38]. Of primary importance, the device’s rich array of input peripheral technologies affords novel methods of interaction.

Insert figure 1 about here

By using the Wiimote’s orientation tracking technologies (accelerometer and infrared camera) to describe a virtual counterpart within the VE, the system allows the real world device to function as both a cane and a handheld camera within the VE. Interface with the VE is achieved through use of the Windows-based Wii Controller Interface Suite (WiiCi). WiiCi is a collection of tools written in C# [39] that utilises an enhanced version of Peek's Managed Library for Nintendo's Wii remote [40] to allow for the successful connection and interface between PC and Controller. The tools provide the ability to map the Wiimote’s input peripherals, such as button presses and accelerometer-recorded movement, in addition to those of standard human interface devices, such as a keyboard, mouse, and joystick. In effect, this capability enables the Wiimote to be seen by the system as any of the highlighted devices and is only limited by the volume of inputs available from the device.

The participants were seated next to the computer to which the device was connected and held the Wiimote and the Nunchuck in both of their hands to move it and get additional information about the objects' names and locations. They received this auditory feedback via stereo headphones (Figure 2).

Insert figure 2 about here

The system works by enabling the Wiimote to be used as a tool that can scan the environment in front of the user (look-around mode), or the Nunchuk to be used to direct motion (walk-around mode).

Look-around mode

The Wii Controller is used for scanning for objects in the space; this look-around mode is available to people who are blind only in this suggested virtual reality system. In real life few people who are blind use obstacle detectors or a laser long cane, which provides auditory information (like a sonar) about the existence of an object without information about the type of object or its exact distance. The look-around mode is achieved through the movement and orientation of the virtual controller; thus the view of the environment is directly slaved to that of the Wii Controller.

As a result of this interaction, the user receives auditory and haptic feedback via the operating system. The audio cues indicate different types of objects and their distance. Different tones of beep indicate furniture, walls, doors, and floors. A force feedback rumble is triggered and varied according to the distance (determined via ray-casting from the point of reference of the virtual Wii Controller) to an object. A constant rumble is triggered on collision with an object or the environment.

Indication that a user is out of the look-around mode is provided in the form of a constant rumble. Transition from one defined space to another is indicated with a whooshing sound. Pressing buttons (Wii Controller button 1) produces spoken distance and the name (Wii Controller button 2) of the object currently detected by the ray-cast. In addition, upon entrance to a VE, a description of the space becomes available via another button press (Wii Controller button Home).

Walk-around mode

Forward and backward motion is initiated by tilting the Nunchuck in a forward or backward direction. This action is accompanied by a representative audio cue indicating footsteps. The speed of this motion is dependent upon the severity of tilt. Similarly, left and right turning is achieved by rolling the Nunchuck to the left or to the right. This action produces a fixed 15-degree turn within the VE in accordance with tilt direction. Upon the activation of a turn, individual left and right audio cues are triggered to provide an indication that the turning action is being performed.

Methods

Participants

The study included 10 participants. The participants were selected based on six criteria: totally blind, trained in O&M, English as a second language understanding, having onset of blindness at least two years prior to the experimental period with no additional impairments, and familiarity with computer use. We defined two groups—experimental and control—that were similar in age, gender, age of vision loss (congenitally or adventitiously blind), and use of O&M aids such as a long cane or guide dog. Each research group had five participants. The 10 participants were congenitally or adventitiously blind without residual vision, were students or employees from all over Israel, and felt comfortable using computers (Table 1). The experimental group participants explored the unknown space by means of the VE and Wii Controller. The control group participants independently explored the unknown space by walking in the RS. The research participants were recruited by snowball sampling and randomly assigned to the experimental or control group. To evaluate the participants' initial O&M skills, the researchers asked all participants to individually complete a questionnaire on O&M issues. The questionnaire results showed no differences in initial ability among participants in either group. In familiar indoor spaces (their home or work space) none of the participants used a mobility aid; in familiar indoor (small or large shopping mall) most of the participants (70%) preferred to be accompanied by a sighted person; in familiar outdoor spaces (their neighborhood with street crossing, public transportation) most of the participants (70%) used their mobility aid (long cane or guide dog); in familiar crowded outdoor and unfamiliar indoor spaces the participants preferred to use their mobility aid or to be accompanied by a sighted person; in unfamiliar indoor spaces such as shopping areas and unfamiliar outdoor spaces most of the participants (70-100%) preferred to be accompanied by a sighted person.

Insert table 1 about here

Due to the exploratory nature of this study, the challenges faced in recruiting participants, and the logistics involved in running the tests (where the experimental group required some six repeated sessions including four training sessions), participants were limited to 10 subjects. As a result of this small sample we could not run statistically significant tests, but the research data present and express differences that in the future can be tested with a larger sample in several areas of interest raised by the data.

Variables

The independent variable in this research was the complexity of spaces explored by the participants, including a simple and a complex environment. The environment level of complexity was dependent on environments' size, structure, and number of components, which were all examined by the O&M rehabilitation specialist. Three groups of dependent variables were defined: the process of the exploration task, construction of a mental map, and performance of orientation tasks in RS. These variables were defined in our previous research [41, 12].

Exploration process

Five variables were related to the exploration process: (1) total duration: the total time spent accomplishing the task; (2) exploration modes: the walk-around mode (exploring the space by navigating the avatar in the space), or look-around mode (exploring the space by standing in one spot and getting information as requested about the object name, object distance, space structure name, or space structure distance); (3) spatial strategies used by participants in their exploration: perimeter strategy (walking along a room's walls), grid strategy (exploring a room's interior), object-to-object strategy (walking from one object to another), exploring object area strategy (walking around an object and exploring the space around it), and random strategy (walking without pattern); (4) the number of pauses taken by the participant during the exploration, not as a result of technical issues and of more than five seconds; and (5) the use of the second hand as an orientation aid to explore the spaces.

Mental map construction

The construction of a mental map process included eight variables: (1) structural component; (2) structural components' location; (3) object within the space; (4) objects' location(s); (5) spatial strategy used for describing the space: perimeter, object-to-object, items list, or starting-point perspective descriptions; (6) spatial model used for describing the space: route model in which the environment is described in terms of a series of displacements in space, map model as a holistic overall description of the space, and integrated representation of route and map models; (7) chronology of the descriptive process; and (8) spatial relationship verbal descriptions that related an object to a structure or to another object by distances or directions.

Orientation task performance

This group of variables examined the participants' performance on the orientation tasks in the RS. Five variables were related to the orientation tasks performance: (1) total duration was the total time spent accomplishing the task; (2) successful completion defined by the participant's ability to find the task's target in the RS: good navigation, arrived at the target's zone, arrived at the target's zone with verbal assistance, or failed; (3) type of path, defined as the path that the participant chose to take: direct, direct with limited walking around, indirect, or wandering around; (4) spatial strategies, defined by alternative strategies used by the participants in their navigation: perimeter, grid, object-to-object, exploring object area, or other strategies; and (5) orientation aids that participants used, such as using their second hand, object landmark, audio landmark, cardinal direction, verification of starting point, reversing to starting point, or traveling toward more spatial information.

Instrumentation

The research included two implementation tools and five data collection tools.

The two-implementation tools are described below.

Simulated environments

This research included RSs located at the School of Education at the Tel Aviv University campus. To examine the effect of learning as a result of the exploration task in the Wii system, two unfamiliar indoor spaces were chosen. These RSs differed in their level of complexity (size, structure, and number of components). An O&M rehabilitation specialist helped the researchers to choose and to define simple and complex environments from the O&M perspective. The simple environment (Figure 3) was a rectangular shape of 44 square metres, with five doors (the light green lines represent private doors) and two windows and nine objects (dark green): a communication cabinet (item 1); an electric cabinet (item 2); two mailboxes (items 3 and 4); a chair (item 5); one bench (item 6); a recycling bin (item 7); and two boxes (items 8 and 9). The complex environment (Figure 4) was bigger, in a ladder formation (two long parallel corridors at each side and two short corridors in between), and had four areas and 11 objects in it. The light green and red lines in the figure below represent public and private doors (see Figure 4, items 10 and 11). The dark green in the figure below represents structural and object components, such as two benches (items 1 and 7); stairs going down (item 2); recycling bin (item 3); snack machine (item 4); two round tables (items 5 and 6); chair (item 8); mailbox (item 9); window (item 12); electric cabinet (item 13); pole (item 14); and box (item 15). The RSs and VEs were the same. Because of safety and O&M issues these simulated environments were chosen in conjunction with an O&M rehabilitation specialist.

Insert Figures 3 and 4 about here

VE Wii-based system training environments

Eight different VEs were built for training the experimental participants on how to use the VE Wii-based system (Figure 5). The VEs differed in their level of complexity (size, structure, number, and location of components).

Insert Figure 5 about here

O&M questionnaire

The questionnaire aimed to evaluate the participants' O&M experiences, abilities, and self-evaluation of O&M ability. The questionnaire contained 50 items concerning the participant's O&M abilities indoors and outdoors as well as in known and unknown environments. The O&M questionnaire was taken from previous research [41, 12; 42, 43]. This O&M questionnaire was itself evaluated by four O&M rehabilitation specialists.

Exploration task

To replicate the way people who are blind investigate a new space, all participants were asked to freely explore the simple and the complex spaces. The experimental group explored them via the VE Wii-based system and the control group explored the RS. Participants were instructed to learn the space in their own way in a limited time that was recommended by an O&M rehabilitation specialist (40 min for exploring the simple space and 60 min for exploring the complex space).

Description task

After exploring the environment, participants were asked to describe the environment verbally. This description tasks were video recorded and transcribed.The verbal description was a tool for understanding the mental map the participants constructed as a result of the exploration task. The verbal description task was chosen as opposed to a physical model construction task to negate any learning effects that could accrue from the act of construction.

Orientation tasks in the RS

All participants were taken to the RSs (simple and complex) to perform five orientation assignments: (1) two Object-Oriented assignments in which the participants were asked to go to an object from the original exploration starting point (for example, from the starting point please go to the bench); (2) two Perspective-Change assignments in which the participants were asked to go from a new starting point to an object (for example, from this new point please go to the window); and (3) Point-to-the-Location assignments, in which the participants were asked to point to six different structural or object components from the exploration starting point (for example, from the starting point please point to the location of large mailbox, chair, etc).

In addition to the above four implementation tools, a set of three data collection tools was developed for the collection of quantitative and qualitative data, as follows.

Observations

During the VE Wii-based system exploration the experimental participants were video recorded and their activity in the VE was also screen recorded. The participants' video was recorded and their VE screen recordings were synchronized in real time on the researcher's computer by using Camtasia 2 (screen recording software). The control group participants were video recorded in the RS exploration tasks. Both research groups were video recorded during the orientation tasks in the RS.

Data analysis

To evaluate the participants' O&M performance in the experiments, we applied coding schemes that were mostly developed in previous research studies by four O&M rehabilitation specialists with 15 years of experience in a rehabilitation centre for people who are blind [24, 44]. Based on the five research data collection tools (O&M questionnaire, exploration task, description task, orientation tasks in the RS, and observations), previous analyses, and O&M literature [5, 45, 8], we designed and built coding schemes with the O&M rehabilitation specialists (prior spatial knowledge, process of exploration task, and RS orientation tasks performance). The data were analysed using quantitative software Microsoft Excel ® and the participants' recordings (video, transcriptions, and computer logs) were coded and analysed at the same time using Interact version14, a qualitative statistical software.

Procedure

The procedure in this research was based on earlier work that examined the construction and use of mental maps after exploring VEs [41]. All participants explored the VE and RS and were observed individually. The participants from the experimental group had a total of six meetings of 90 min each: four meetings to learn how to use the system with confidence and two experimental meetings. The control group participants had two experimental meetings of 90 min each. In the first session all participants signed the consent form and completed the O&M questionnaire. Next, the experimental participants learned to operate the VE Wii-based system for exploring the VEs and gained confidence in using it (four sessions of 90 min each); as evidenced by other researchers [12, 46], these first four sessions were necessary to ensure fair comparison between the groups. The next two sessions were dedicated to exploring the simple and complex environments (the experimental group using the VE Wii-based system and the control group exploring the RSs). After the exploration task the participants described the space and later performed orientation tasks in the RSs. All participants carried out the same orientation tasks in the RS and in the same order.

Results

Research Question 1: What exploration strategies and processes do people who are blind use when working with the VE Wii-based system in the experimental and the RS in the control groups?

Both research group participants explored the VE or the RS independently. To explore the simple space, the experimental participants used an average of 00:41:44 min to explore the VE. Three of the participants used less time than the suggested exploration time, and the other two participants asked for more time. The control participants used an average of 00:04:39 min, about ten times less compared with the experimental group. The participants in the experimental group were able to implement the look-around and walk-around modes differently than did the participants in the control group, who were able to implement the walk mode only. As a result of these differences the two groups applied different exploration strategies (Table 2). The results showed that the experimental group mainly used the point mode to explore the environment. The participants in the experimental group used the look-around mode for an average of 74% of their exploration time, paused for 17% of the time, and walked around in the VE for only 9% of the time. The total look-around mode data was coded and analysed using four different variables: look-around mode-object-name, look-around mode-object-distance, look-around mode-space-name, and look-around mode-space-distance. This separation aimed to help the researcher understand the participants' exploration strategies. The results showed that in 40% of the total look-around mode duration the participants used look-around mode-name (by look-around and eliciting the object name, with accompanying auditory feedback), and 34% of the time they used look-around mode-distance (by pointing and eliciting distance information, with audio feedback describing the number of steps between the object and the participant's location). In addition, when participants collided with a component, they preferred more information about the distance to the component in front of them to knowledge of its name; however, when they pointed, they checked the component's name more often than its distance. Although the VE Wii-based system allows the look-around mode to indicate different heights, only one participant used this feature and then only for a few seconds. The spatial strategy that was most used was the object-to-object strategy (Table 2). In comparison, the control group participants used the walking mode for 94% of their exploration time in the RS and used only 6% of their exploration time for pauses. They mainly used the perimeter strategy, for which only 6% of their exploration time was used for pauses. During 52% of their exploration time the control group members used their second hand to explore the RS. This ability to explore the space using the second hand was not possible in the VE for the experimental group participants.

Insert Table 2 about here

To explore the complex space, the experimental participants used an average of 53:19 min to explore the VE. The control participants used an average of 9:14, about six times less compared with the experimental group (Table 3). The exploration mode results showed that the experimental group mainly used the look-around mode. The participants used the look-around mode an average of 73% of their exploration time, took 15% of their exploration time for pauses, and spent only 12% of their exploration time walking in the VE. The spatial strategy that was most used was the object-to-object strategy (Table 3). The total look-around mode data was coded and analysed by look-around mode-object-name, look-around mode-object-distance, look-around mode-space-name, and look-around mode-space-distance. The results showed that in 43% of the total look-around mode duration the participants used look-around mode-name, and 29% of the time they used look-around mode-distance. In comparison, the control group participants implemented the walking mode for 99% of their exploration time in the RS, mainly using the perimeter strategy, and using only 1% of their exploration time for pauses. During 43% of their exploration time they used their second hand to explore the RS. Again, the ability to explore the space using the second hand was not available to the experimental group participants.

Insert Table 3 about here

A comparison of behavior in the two research spaces shows that the two groups divided the exploration time almost equally among the same methods in the simple environment and in the complex environment. This comparison highlights two main differences: exploration duration and spatial strategies. The experimental group took six to 10 times longer than the control group in each space. The use of spatial strategies was different with the choice of strategies: the participants in the control group used mainly the perimeter strategy, while the experimental group mainly used the look-around mode and object-to-object strategy, with the perimeter as their secondary strategy, as mentioned earlier.

Research Question 2: What were the participants’ mental mapping characteristics in the experimental and control groups?

To answer this question we examined the participants' verbal descriptions. The variables we examined were: structural component, structural component location, object, object location, spatial strategy, estimated relationship between the spaces’ components, spatial representation model, and chronology description.

We examined the descriptions of the simple (Table 4) and the complex (Table 5) spaces in both research groups. For the simple environment, the experimental participants mentioned in their description an average of 69% of the total components that were located in the environment, compared to 40% for the control participants. The participants included in their verbal descriptions more objects than structural components. The participants used all types of spatial strategies to describe the space. The participants included space components' relationship information in their verbal descriptions, such as 'on the same wall' and 'when I am behind door 214, the bench is on the left side'. The experimental participants embedded in their verbal descriptions an estimated relationship description of at least 10 sentences in such descriptions, compared to only five sentences by the control participants. The verbal descriptions by four experimental participants were based on a map model, compared to the control group in which four participants used route model and one used map model. All research participants started their descriptions by mentioning a structural component.

For the complex environment (Table 5), the experimental participants mentioned in their verbal descriptions an average of 44% of the total components that were located in the environment, compared to 30% for the control participants. The participants included in their verbal descriptions more objects than structural components. The participants used all types of spatial strategies to describe the space. The experimental participants embedded in their descriptions an estimated relationship description of at least nine sentences that included such descriptions, compared to seven sentences by the control participants. In the experimental group's verbal descriptions two participants employed a map model and two participants used a route model; one participant listed them. Similar results were found in the control group, where two participants used a map model and three participants used a route model. Most of the research participants started their descriptions by mentioning a structural component, except for one participant from the control group, who started his description with the content description.

Insert table 4 and 5 about here

The results show a difference between the two research groups and both environments. The experimental participants' verbal descriptions were described in greater detail, and they embedded more estimated relationship sentences for both environments. In describing the simple environment, four experimental participants constructed a map model; however, when describing the complex environment, only two participants constructed a map model. Participants in both research groups described the simple environment in more detail than they did the complex environment.

Research Question 3: How did both research groups perform orientation tasks in the RSs?

In answering the third question, the participants' orientation tasks performances in the RS were examined. The orientation tasks included: Object-Oriented tasks, Perspective-Change tasks, and a Point-to-the-Location task. In the simple environment the participants performed three Object-Oriented tasks and three Perspective-Change tasks (Table 6) and in the complex environment they performed two Object-Oriented tasks and two Perspective-Change tasks (Table 7). These tasks were evaluated by duration, success in the task, the path that was chosen, the spatial strategy adopted, and the aids used.

In the simple environment, the experimental group participants took five times more time to complete the Object-Oriented tasks (Table 6), and four times more time to complete the Perspective-Change tasks. Similar results were found between the two research groups for the next three variables. In performing Object-Oriented tasks, 74% of the experimental participants succeeded in arriving at the target and 73% of the control participants succeeded in arriving at the target, and in Perspective-Change tasks 60% of the experimental participants and 73% of the control participants succeeding in arriving at the target. Regarding the type of path, in 53-60% of performances the experimental participants walked directly to the object, compared to 67% for the control group. Both research groups used mainly the perimeter strategy and secondly the object-to-object strategy. Differences between the research groups were found in using spatial tools (using their second hand to support orientation and landmarks) and orientation problem-solving tools, such as stop and think, going back to starting point, or verifying the starting point. The experimental participants used their second hand to support orientation in 35-40% of task duration compared to 20-24% for the control participants' time. During the task performances in eight trails, experimental participants used landmarks (audio and object) compared with only two trails used by control participants. Regarding orientation problem-solving tools the experimental participants applied more tools during their performance compared with the control group. During task performances the experimental group participants used stop and think about the task for 25-28% of their task time, compared with 0-2% of the control group task time. Of the experimental participants, 30% walked back to the known starting point or verified their starting point location compared to 7% of the control participants. In the Point-to-the-Location task similar results were found for the two research groups, with 83% succeeding in both.

In the complex environment (Table 7), two of the experimental participants stayed in the entrance lobby and did not explore the entire environment. These actions affected the results, as the participants did not know where the objects were located. In their first Object-Oriented task they walked carefully in the space, transforming their VE landmarks in the RS to ground their spatial knowledge. After this process they became more confident, so the orientation task durations grew shorter even when an object was farther away, and even in the

Perspective-Change tasks. The experimental group participants needed twice the time to complete the Object-Oriented and Perspective-Change tasks. Both research groups used mainly the perimeter strategy and secondly the object-to-object strategy. In Object-Oriented tasks 40% of the experimental participants and 50% of the control participants succeeded in performing the orientation tasks, and in Perspective-Change tasks, 60% of the experimental participants and 70% of the control participants succeeded in performing the orientation tasks. In the Object-Oriented tasks the experimental participants used their second hand less often to support orientation, in 24% of their tasks' duration compared to 46% of the control participants' time. In the Perspective-Change tasks the experimental participants used their second hand more often to support orientation, in 46% of task duration compared to 36% of the control participants' time. Because the research took place in a RS and not in a lab, there were ambient sounds that the participants used as landmarks, for example, the sound of a snack machine or students walking and talking in the lobby. Seven experimental participants used landmarks (audio and object) compared to only four control participants. In regard to orientation problem-solving tools, the experimental participants applied more tools during their performance compared with the control group. For 44% (for Object-Oriented tasks) and 27% (for Perspective-Change tasks) of their task time the experimental group used stop and think, compared to 2% (Object-Oriented tasks) and 4% (Perspective-Change tasks) for the control group; 20% of the experimental participants walked back to the known starting point or verified their starting point location (15%) compared with 10% of the control participants. In the Point-to-the-Location task the experimental participants had a success rate of 33% of the time; one of the participants failed this task as a result of a mirror distortion, but the control group had a success rate of 50% in this task.

Insert Tables 6 and 7 about here

Examination of both research groups' participant behavior in the orientation tasks (Tables 6 and 7) finds behavior differences among the participants. Some of the participants in the experimental group and control group were able to apply their exploration knowledge in the simple and complex environments in both orientation tasks. Other participants in both research groups expressed difficulties in applying their spatial knowledge in the Perspective-Change tasks.

Discussion

The study reported here is part of a research effort aimed at examining the use of a VE Wii-based system to support users in collecting information and constructing a mental map of the research spaces that were used later in the RS. This is also the first research study to examine the use of the look-around mode to explore new spaces within a VE. The results of this study help to elucidate three main issues concerning the contribution of the virtual cane to the exploration strategies and the learning processes of new spaces by people who are blind.

Look-around mode

To explore unknown RSs independently, people who are blind usually walk in the space, using predominantly the perimeter strategy, followed by the grid strategy [5]. Most of the O&M VEs that have been developed for people who are blind replicate this behavior [12, 15].

The virtual cane based on the Wii system offers a new choice – the look-around mode. This option affords the users the ability to stand in place and to point at the space's components. This ability allows the user to collect information about the object's identity and its distance from the user without the need to walk to it. In RS people who are blind can employ this mode partially by using special obstacle detectors. These devices, such Miniguide [47] or Palmsonar [48], enable users who are blind to detect only the appearance of objects that are nearby; they cannot identify their names or distances. This look-around mode is unique to the virtual cane. The research results show that during their exploration the experimental participants mainly used the look-around mode. Using this mode requires users to establish a complex collecting and processing procedure for the spatial data, which takes more time but subsequently allows them to apply this knowledge in the RS. Collecting spatial information by using the look-around mode is extremely difficult, especially for people who are blind. People with sight, who use a similar strategy, are able to easily locate two or more landmarks in a space at the same time and to build relative references between them by using the triangulation method [49]. In comparison, a person who is blind needs to collect each landmark separately and to place them all together in his or her mental map, and this process is a cognitively very complex task. On the other hand, using the look-around mode enables the user to divide the space into small areas by looking around at the surrounding objects from one location, and this exploration process allows the user to learn each area separately. A similar process appears in the decomposition process in complex systems. The decomposition process is the process of understanding the relationship of smaller classes in a way that the whole can be reconstructed from the parts [50].

The choice of the look-around mode by the experimental participants might have occurred as a result of their motivation to use a new exploration strategy, but it might also have been that during the use of the new look-around mode they realized that they were able to use it to construct a mental map. The use of this new look-around mode is expensive from a time perspective, with the experimental participants (mainly two participants) using six to 10 times longer than the control group in each space. Other research on this topic [12] supports this finding, where participants used four times longer to explore the VE compared with the same RS. Nevertheless, the experimental participants used more pauses during the exploration (pauses not based on technical issues). The use of this new exploration strategy (look-around mode) resulted in the users' requesting more processing time for their data collection processes and the construction of a mental map. Acquiring more experience with the look-around mode might reduce processing time in future use.

When the experimental participants chose the walk mode, object-to-object was the main spatial strategy and perimeter was secondary, while the findings for the control group and findings of other research show that participants walked mostly using the perimeter strategy and walking was the main tool of exploration [12, 15, 24].

Both research groups achieved the same success in the RS. Although the mental map was less detailed as the spaces became more complex, the participants still managed to perform most of the tasks in the corresponding RS. The look-around mode used by the experimental participants allowed them to apply their spatial knowledge in the RS accordingly and to achieve the same success as the control group members, who used the direct path and the perimeter strategy as their spatial strategies.

Mental map

Both research groups were able to construct a mental map. As the spaces became more complex, the mental map was less detailed. A future study should examine these changes in spatial representation and should consider the use of an outdoor environment. The research results for this study show that the experimental participants were able to construct a more holistic mental map with more detail and information regarding the space compared to the control group. Sighted people can choose one of two spatial models according to their spatial needs: route and/or map model. The route model is based on linear recognition of spatial features, while the map model is holistic and encompasses multiple perspectives of the target space [34]. One of the strengths of constructing a mental map that is based on a map model is the flexibility in choosing the path according to changes that occur in the space, such as road construction, traffic problems, or other emergency situations. A map model user will be able to switch easily to a new path without the need to walk to the starting point and figure out a new path from there. Research on spatial models has shown that people who are blind mainly use the route model when navigating in spaces and sighted people mostly code spatial information in holistic, externally based representations [35, 36]. Similar results have emerged in previous research on the construction of a mental map by people who are blind after exploring a VE [44]. People who are blind are trained to use mainly the route model, especially in the beginning of their O&M rehabilitation program. In the current study people who are blind chose to represent their mental map using a map model, raising a new research question – whether new technology can have an impact on participants' mode of exploration and whether the way they collect spatial information affects the way they represent their mental map. In both simple and complex spaces, 60% of the experimental participants constructed mental maps that were based on the map model, compared to 30% of the control group participants. It is hypothesised that the look-around mode of the virtual cane affords the multiple references between the target space components to help generate these more detailed map model spatial representations, allowing a user who is blind to gather information in the way a sighted person would in the RS – via multiple lines of sight. Sensory substitution of the sight-based information occurs, and the map model spatial representation is generated via haptic and audio feedback.

Implications for researchers and developers

Further research should carefully explore the look-around mode, the new exploration strategy that is afforded by the virtual cane. To determine the influence of the look-around mode on the participants' spatial ability in RS, it will be valuable to compare the spatial ability of two experimental research groups using the virtual cane (i) with look-around mode only and (ii) with walk-around mode only. It will be important to examine the exploration process that is based on the decomposition process and its impact on the exploration process and on the construction of a mental map based on a map model spatial representation. Moreover, it will be interesting to understand how the look-around mode VE exploration aids people who are blind in O&M tasks that involve spatial problems that are based on map model knowledge solutions, particular situations such as, path blocked and the necessity to find alternative path.

Future development of the virtual cane system will need to focus on the user's training process. Walking in the VE Wii-based system required extensive training to develop the required exploration skills, as participants had to develop exploration skills and strategies that were new and different compared to those used in a RS. In response, a new generation of virtual canes has been designed. One is based on commercially available wearable technology [51] and combines Orientation Mobility Cane Techniques (OMCT) and the Walking in Place (WIP) technique -- an established and effective method for navigation within a VE. It enables an individual to navigate within a VE without the physical limitations imposed by tracking devices and via a mechanism closer to the RS method of walking compared with the previous generation of the virtual cane. The second is a technologically augmented assistive cane [15], which equips a cane with capability to act as an input and output peripheral for contemporary mobile technologies. This capability not only allows the operator to navigate with a cane within a VE, but also affords assisted and augmented real world navigation.

The encouraging results of the current study indicate the potential strengths of the VE for those who are congenitally or adventitiously blind. Nevertheless, the virtual cane is affordable and ubiquitous technology, which can be used in a range of rehabilitation contexts (blind services, independent use, etc.). After further research, the virtual cane Wii-based system could play a central role in two main potential applications. It could be used as a training aid in the rehabilitation process, or it could support a learning environment to provide familiarity with unfamiliar spaces, where the ability to orient oneself independently is essential to carrying out life tasks. The opportunity to practice navigating around environments and traveling in a safe VE builds knowledge, experience, and confidence in people who are blind [44].

In this experiment we have compared training in the VE Wii-based system with RS training. The results are broadly similar, and indeed the former afforded the development of a map-based mental model in a greater number of participants. Participants in previous studies have reported that people who are blind can find it difficult to access O&M training in the real world (because of lack of availability of trainers, cuts in services, etc.), and so alternative (virtual) and equally effective methods that can augment real world services are called for. Other studies have highlighted the importance of reducing reliance on guides [23], and this experiment demonstrates one avenue to that goal.

References

[1] Lynch K. The image of the city. Cambridge (MA): MIT Press; 1960.

[2] O'Keefe J, Nadel L. The hippocampus as a cognitive map. Oxford (UK): Clarendon Press; 1978.

[3] Foulke E. The perceptual basis for mobility. Research Bulletin of the American Foundation for the Blind. 1971;23:1–8.

[4] Clark-Carter D, Heyes A, Howarth C. The effect of non-visual preview upon the walking speed of visually impaired people. Ergonomics 1986;29:1575–81.

[5] Jacobson WH. The art and science of teaching orientation and mobility to persons with visual impairments. New York: American Foundation for the Blind; 1993.

[6] Golledge RG, Klatzky RL, Loomis JM. Cognitive mapping and wayfinding by adults without vision. In: Portugali J, editor. The construction of cognitive maps. Dordrecht (Netherlands): Kluwer Academic; 1996. p 215–46.

[7] Ungar S, Blades M, Spencer S. The construction of cognitive maps by children with visual impairments. In: Portugali J, editor. The construction of cognitive maps. Dordrecht (Netherlands): Kluwer Academic; 1996. p 247-73.

[8] Hill E, Rieser J, Hill M, Hill M, Halpin J, Halpin R. How persons with visual impairments explore novel spaces: Strategies of good and poor performers. Journal of Visual Impairment and Blindness 1993; 87:295-301.

[9] Porathe T. Measuring effective map design for route guidance: An experiment comparing electronic map display principles. Information Design Journal 2008;16:221-4.

[10] Kitchin RM. Cognitive maps: What are they and why study them. Journal of Environmental Psychology 1994;14:1-19.

[11] Chebat DR, Schneider FC, Kupers R, Ptito M. Navigation with a sensory substitution device in congenitally blind individuals. Neuroreport 2011; 22: 342–347. doi: 10.1097/WNR.0b013e3283462def. pmid:21451425.

[12] Lahav, O., Mioduser, D., 2004. Exploration of Unknown Spaces by People Who Are Blind Using a Multi-sensory Virtual Environment. *Journal of Special Education Technology, 19*, 15-23.

[13] Arons B. A review of the Cocktail Party effect. Journal of the American Voice I/O Society 1992;12:35–50.

[14] Kincaid JP, Hamilton R, Tarr RW, Sangani H. Simulation in education and training. In: Obaidat MS, Papadimitriou GI, editors. Applied System Simulation. Norwell (MA): Kluwer Academic Publishers; 2003. p 437-56.

[15] Lahav, O., Schloerb, D. W., Srinivasan, M. A., 2015. Rehabilitation Program Integrating Virtual Environment to Improve Orientation and Mobility Skills for People Who Are Blind. *Computers and Education, 80*, 1-14, Elsevier.

[16] Cromby JJ, Standen PJ, Brown DJ. The potentials of virtual environments in the education and training of people with learning disabilities. Journal of Intellectual Disabilities Research 1996;40:489-501.

[17] Semwal SK, Evans-Kamp DL. Virtual environments for visually impaired. In: Heudin JC, editor. Lecture Notes in Artificial Intelligence 1834, Subseries of Lecture Notes in Computer Science, The 2nd International Conference on Virtual Worlds; 2000 July 5-7; Paris, France. Springer; 2000. 270-284 p.

[18] Sjotrom C, Rassmus-Grohn K. The sense of touch provides new computer interaction techniques for disabled people. Technology Disability 1999;10:45–52.

[19] Karshmer AI, Bledsoe C. Access to mathematics by blind students—Introduction to the special thematic session. In: Miesenberger K, Klaus J, Zagler W, editors. The International Conference on Computers Helping People with Special Needs (ICCHP); 2002; Berlin/ Heidelberg (Germany): Springer-Verlag; 2002. p 471–6.

[20] Van Scoy F, Kawai T, Darrah M, Rash C. Haptic display of mathematical functions for teaching mathematics to students with vision disabilities: Design and proof of concept. Haptic human–computer interaction, Lecture notes in computer science; 2000. Springer LNCS, 2058, p 31–40.

[21] Van Scoy F, McLaughlin D, Fullmer A. Auditory augmentation of haptic graphs: Developing a graphic tool for teaching precalculus skill to blind students. The 11th Meeting of the International Conference on Auditory Display; 2005; Limerick, Ireland.

[22] Yu W, Ramloll R, Brewster SA. Haptic graphs for blind computer users. In: Brewster SA, Murray-Smith R. editors. Lecture notes in computer science. The Haptic Human-Computer Interaction. The 1st International Workshop, 2058; 2001. Berlin (Germany): Springer; 2001. p 41–51.

[23] Evett, L., Battersby, S. J., Ridley, A., Brown, D.J., 2009. An interface to virtual environments for people who are blind using Wii technology - Mental models and navigation. *Journal of Assistive Technologies, 3*, 26-34.

[24] Lahav, O., Schloerb, D. W., Srinivasan, M. A., 2012. Newly blind persons using virtual environment system in a traditional orientation and mobility rehabilitation program: A case study. *Disability and Rehabilitation: Assistive Technology, 7*, 420-435.

[25] Max ML, Gonzalez JR. Blind persons navigate in virtual reality (VR): Hearing and feeling communicates “reality.” In: Morgan KS. et al., editors. Medicine meets virtual reality: Global healthcare grid. San Diego (CA): IOS Press; 1997. p 54-9.

[26] Merabet L, Sánchez J. Development of an Audio-Haptic Virtual Interface for Navigation of Large-Scale Environments for People Who Are Blind. Lecture notes in computer science. 10th International Conference, UAHCI 2016, Held as Part of HCI International 2016; 2016. Toronto, ON, Canada: Springer; 2016. p 595-606.

[27] Ohuchi M, Iwaya Y, Suzuki Y, Munekata T. Cognitive-map formation of blind persons in virtual sound environment. The 12th International Conference on Auditory Display; 2006 June 20-23; London, UK.

[28] Pokluda L, Sochor J. Spatial haptic orientation for visually impaired people. The Eurographics Ireland Chapter Workshop Series; 2003; University of Ulster, Coleraine, UK.

[29] Sánchez J, Lumbreras M. Usability and cognitive impact of the interaction with 3D virtual interactive acoustic environments by blind children. The 3rd International Conference on Disability, Virtual Reality and Associated Technologies; 2000 September 23-25; Alghero, Italy.

[30] Simonnet M, Vieilledent S, Jacobson DR, Tisseau J. The assessment of non-visual maritime cognitive maps of a blind sailor: A case study. Journal of Maps 2010;6:289-301.

[31] Picinali L, Afonso A, Denis M, Katz BFG. Exploration of architectural spaces by blind people using auditory virtual reality for the construction of spatial knowledge. International Journal of Human-Computer Studies 2014;72:393-407.

[32] Seki Y, Ito K. Study on acoustical training system of obstacle perception for the blind. Assistive Technology Research Series 11, Assistive Technology -- Shaping the Future; 2003; Dublin, Ireland. p 461-5.

[33] Seki Y, Sato T. A training system of orientation and mobility for blind people using acoustic virtual reality. IEEE Transactions on Neural Systems and Rehabilitation Engineering 2011;19:95-104.

[34] Siegel AW, White SH. The development of spatial representations of large scale environments. In: Reese HW, editor. Advances in child development and behavior. New York: Academic Press; 1975. p 10-55.

[35] Fletcher JF. Spatial representation in blind children 1: Development compared to sighted children. Journal of Visual Impairment and Blindness 1980;74:318-85.

[36] Noordzij ML, Zuidhoek S, Postma A. The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions. Cognition 2006;100: 321-42.

[37] Lloyd R. Cognitive maps: Encoding and decoding information. Annals of the Association of American Geographers 1989;79:101-24.

[38] Battersby, S., 2008. The Nintendo Wii controller as an adaptive assistive device–a technical report. *Proceedings of the HEA ICS Supporting Disabled Students through Games Workshop*. Middlesbrough, UK.

[39] Battersby, S., 2013. *A flexible object orientated design approach for the realisation of assistive technology*. Unpublished doctoral dissertation, Nottingham Trent University.

[40] Peek B. Managed library for Nintendo's Wiimote. (2008). [cited 2015 May 29]. Available from: http://www.brianpeek.com.

[41] Lahav, O., 2003. *Blind persons' cognitive mapping of unknown spaces and acquisition of orientation skills, by using audio and force-feedback virtual environment*. Unpublished doctoral dissertation, Tel-Aviv University.

[42] Dodson-Burk B, Hill EW. Preschool orientation and mobility screening. A publication of Division IX of the Association for Education and Rehabilitation of the Blind and Visually Impaired. New York: American Foundation for the Blind; 1989.

[43] Sonn U, Tornquist K, Svensson E. The ADL taxonomy -- From individual categorical data to ordinal categorical data. Scandinavian Journal of Occupational Therapy 1999;6:11-20.

[44] Lahav, O., Mioduser, D., 2008. Construction of cognitive maps of unknown spaces using a multi-sensory virtual environment for people who are blind, *Computers in Human Behavior 24*, pp. 1139–1155.

[45] Jacobson RD, Kitchin R, Garling T, Golledge R, Blades M. Learning a complex urban route without sight: Comparing naturalistic versus laboratory measures. The International Conference of the Cognitive Science Society of Ireland, Mind III; 1998; University College, Dublin.

[46] Evett, L., Brown, D.J., Battersby, S.J., Ridley, A., Smith, P., 2008. Accessible virtual environments for people who are blind - creating an intelligent virtual cane using the Nintendo Wii controller. *Proceedings of the 7th International Conference on Virtual Rehabilitation (ICVDRAT)*. Maia, Portugal.

[47] GDP Research. The Miniguide ultrasonic mobility aid. 2005 - [cited 2015 May 29]; Available from: http://www.gdp-research.com.au/minig_1.htm

[48] Takes Corporation. Owner's Manual: Palmsonar PS231-7. 2007 - [cited 2015 May 29]; Available from: http://www.palmsonar.com/231-7/prod.htm

[49] Wikipedia. Triangulation. 2015- [cited 2015 May 29]; Available from: http://en.wikipedia.org/wiki/Triangulation

[50] Talis V. *Comparison between procedural and declarative approach for learning control concepts by students of the technology education* [dissertation]. Tel Aviv (Israel): Tel Aviv University; 2000.

[51] Battersby, S., Brown, D., Lahav, O., 2015. Walking in place with wearable technology: the development of a system for travel training and applied travel for people with a visual impairment. *Proceedings of the Interactive Technologies and Games (ITAG) Conference*. Nottingham, UK.

Table 1.

Research participants.

	Age average	Gender		Age of vision loss		O&M aids	
		Female	Male	Conge-nitally	Advent-itiously	Long cane	Guide dog
Experimental group (*n*=5)	30 (25-40)	3	2	3	2	3	2
Control group (*n*=5)	40 (27-56)	1	4	2	3	3	2

Table 2.

Exploration process in simple space.

	n	Duration (min)	Pointing mode		Spatial strategy			Pauses	Second hand orientation aid
			Name	Distance	Perimeter	Object to object	Other		
Experimental group	1	29:24	37%	33%	2%	6%	0%	23%	NA
	2	49:39	28%	54%	5%	6%	0%	7%	NA
	3	38:32	41%	33%	0%	3%	0%	22%	NA
	4	58:45	45%	21%	4%	3%	0%	28%	NA
	5	32:18	50%	28%	6%	8%	0%	7%	NA
	Total average	41:44	74%			9%		17%	NA
Control group	1	3:44	NA	NA	87%	0%	3%	10%	90%
	2	11:27	NA	NA	62%	2%	29%	7%	97%
	3	2:01	NA	NA	81%	0%	6%	13%	72%
	4	1:26	NA	NA	100%	0%	0%	0%	7%
	5	4:38	NA	NA	89%	11%	0%	0%	63%
	Total average	4:39	NA			94%		6%	52%

Table 3.

Exploration process in complex space.

	n	Duration (min)	Pointing mode		Spatial strategy			Pauses	Second hand orientation aid
			Name	Distance	Perimeter	Object to object	Other		
Experimental group	1	26:36	51%	22%	1%	7%	0%	21%	NA
	2	63:11	26%	49%	3%	13%	0%	6%	NA
	3	44:43	46%	32%	2%	2%	0%	16%	NA
	4	86:53	43%	23%	5%	6%	0%	22%	NA
	5	45:13	51%	20%	9%	11%	0%	7%	NA
	Total average	53:19	73%			12%		15%	NA
Control group	1	7:18	NA	NA	78%	6%	15%	0%	76%
	2	19:23	NA	NA	82%	0%	18%	0%	100%
	3	10:05	NA	NA	84%	3%	9%	0%	4%
	4	3:01	NA	NA	100%	0%	0%	0%	4%
	5	6:24	NA	NA	68%	0%	23%	9%	60%
	Total average	9:14	NA			99%		1%	43%

Table 4.

Verbal description process of simple space.

	n	Space components	Spatial strategy	Estimated relationship	Spatial representation	Chronology
Experimental group	1	66%	List	4	Map model	Structure
	2	79%	Starting point	11	Map model	Structure
	3	68%	Perimeter	13	Route model	Structure
	4	72%	Perimeter & Object-to-object	10	Map model	Structure
	5	62%	Starting point & Object-to-object	14	Map model	Structure
Mean		69%		10	4 Map model	5 Structure
Control group	1	36%	Perimeter	1	Route model	Structure
	2	54%	Area	4	Map model	Structure
	3	27%	Starting point	4	Route model	Structure
	4	15%	List	1	List	Structure
	5	70%	Starting point	14	Route model	Structure
Mean		40%		5	1 Map model	5 Structure

Table 5.

Verbal description process of complex space.

	n	Space components	Spatial strategy	Estimated relationship	Spatial representation	Chronology
Experimental group	1	20%	List	1	List	Structure
	2	46%	Area	9	Route model	Structure
	3	41%	Perimeter	16	Route model	Structure
	4	53%	Perimeter & Object-to-object	10	Map model	Structure
	5	59%	Area	10	Map model	Structure
Mean		44%		9	2 Map model	5 Structure
Control group	1	30%	Starting point	6	Map model	Structure
	2	50%	Area	11	Map model	Structure
	3	30%	Object-to-object	6	Route model	Structure
	4	14%	Starting point & Perimeter	5	Route model	Content
	5	27%	Starting point & Perimeter	7	Route model	Structure
Mean		30%		7	2 Map model	4 Structure

Table 6.

Success in orientation tasks in simple space.

	n	Object-oriented tasks					Perspective-change tasks				
		Duration (sec)	Success	Direct path	Second hand	Stop & think	Duration (sec)	Success	Direct path	Second hand	Stop & think
Experimental group	1	119	67%	33%	21%	56%	74	67%	100%	14%	36%
	2	43	67%	33%	41%	4%	71	67%	67%	29%	16%
	3	93	67%	67%	65%	15%	173	67%	33%	73%	8%
	4	39	67%	67%	21%	23%	83	0	33%	24%	28%
	5	57	100%	100%	28%	44%	192	100%	33%	44%	35%
	AVG	70	74%	60%	35%	28%	119	60%	53%	40%	25%
Control group	1	10	100%	100%	48%	0	29	100%	100%	37%	0
	2	17	100%	67%	27%	0	9	100%	100%	6%	0
	3	17	33%	33%	0	0	44	67%	67%	0	0
	4	9	100%	100%	23%	0	22	67%	33%	46%	11%
	5	13	33%	33%	0	0	61	33%	33%	30%	0
	AVG	13	73%	67%	20%	0	33	73%	67%	24%	2%

Table 7.

Success in orientation tasks in complex space.

	n	Object-oriented tasks					Perspective-change tasks				
		Duration (sec)	Success	Direct path	Second hand	Stop & think	Duration (sec)	Success	Direct path	Second hand	Stop & think
Experimental group	1	110	50%	0	0	67%	302	0	50%	3%	84%
	2	114	50%	0	18%	16%	161	50%	0	16%	0
	3	185	100%	0	48%	10%	320	100%	0	64%	13%
	4	33	0	0	7%	81%	265	50%	0	69%	15%
	5	359	0	0	47%	45%	333	100%	0	77%	21%
	AVG	160	40%	0	24%	44%	276	60%	10%	46%	27%
Control group	1	44	100%	100%	76%	4%	69	100%	50%	74%	13%
	2	14	50%	50%	19%	0	42	100%	100%	0	7%
	3	52	0	0	3%	7%	195	0	0	5%	2%
	4	180	50%	50%	39%	0	65	100%	50%	40%	0
	5	66	50%	50%	93%	0	189	50%	50%	59%	0
	AVG	71	50%	50%	46%	2%	112	70%	50%	36%	4%

Figure captions:

Figure 1. WiiMote and Nunchuck.

Figure 2. The Virtual cane system and the graphic user interface.

Figure 3. The simple environment.

Figure 4. The complex environment.

Figure 5. VE training environments.