The Transfer of Non-Visual Spatial Knowledge Between Real and Virtual Mazes via Sensory Substitution

The Transfer of Spatial Knowledge via Sensory Substitution

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***Abstract*— Many attempts are being made to ease navigation for people who are blind, both in terms of spatial learning and of navigation. One promising approach is the use of virtual environments for safe and versatile training. While it is known that humans can transfer non-visual spatial knowledge between real and virtual environments, limitations of these studies typically include results obtained mainly in simple environments, using mainly blindfolded-sighted participants and different methods of sensory input for real and virtual environments. In this study, participants with a wide range of visual experience use the EyeCane and Virtual EyeCane to solve complex Hebb-Williams mazes in real and virtual environments. The EyeCane and its virtual counterpart are minimalistic sensory substitution devices that code single-point distance information into sound. We test whether participants improve performance in the real-to-virtual sequence: solve a real maze and subsequently improve performance in the virtual maze. We also test whether participants can sole a virtual maze and subsequently improve performance in the virtual world: the virtual-to-real sequence. We find that participants can use sensory substitution guided navigation to extract spatial information from the virtual world and apply it to significantly improve their behavioral performance in the real world and vice versa. Our results demonstrate transfer in both direction, strengthening and extending the existing literature in terms of complexity, parameters, input-matching and varying levels of visual experience.**

Keywords*— Virtual Reality, assistive technology, Sensory Substitution, blind, Congenital Blindness, Low Vision, Acquired Blindness, Visual Rehabilitation, Environmental Rehabilitation, Spatial knowledge, Perceptual Learning, Maze Learning.

I. Introduction

The ability to learn a route and to reproduce it is a perquisite for independent mobility [1]. When learning a new route, or attempting to reproduce an already known route, blind and visually impaired people face several challenges stemming from the absence of visual cues to navigate [2-4]. Many different attempts are being made to alleviate some of the burdens linked to navigation for blind or visually impaired individuals such as the development of sensory substitution devices that transmit visual information through auditory [5] or tactile channels [6-11]. Another major approach to help people who are blind learn routes and navigate them is the development of virtual environments for training and teaching the environmental layouts of specific routes [12]. Virtual environments can offer users a safe way to repeatedly practice spatial interaction with specific environments or to train on new assistive technology without the dangers inherent to real world navigation. Training on the same device in both the real world and virtual environments may help boost performance in everyday life in the real world, and boost accessibility of graphical virtual environments which are currently not accessible to blind and visually impaired users [13].

Sighted people can acquire spatial information from virtual reality training and even apply it to the real world [14-16], or inversely transfer information acquired from a map to navigating inside a virtual reality environment [17]. People who are blind can also learn a route in a virtual reality paradigm [18-19] and transfer knowledge acquired from virtual reality training to navigate more efficiently in the real world [20-22]. This is a particularly important factor in the accurate representation of a spatial layout for people who are blind because virtual training can be misleading. On a complex route for example, and for fast efficient navigation, real-world training has advantages over virtual reality training, as the relative scale of virtual environments may be misleading to judge distances accurately [23, 24]. In the case of blindness misjudging distances in virtual reality environments can lead to the route angularity effect, which is the misinterpretation of the length of a route according to its complexity, or number of turns. In other words, it is hard for people who are blind to judge the scale of distances in virtual environments compared

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to real world distances. Furthermore, the type of information that is used to represent spatial information in a virtual environment for blind people is different from the type of real world cues they use to navigate. In this study, we combine the EyeCane and Virtual-EyeCane to enable us to represent spatial information in the real and in the virtual world using the same perceptual cues. The EyeCane and Virtual-EyeCane code and transmit distances using the same perceptual code: A distance equivalent to one meter in the virtual world is coded and transmitted to the user using the same sounds that a real meter is coded in the real world. This enables users to have corresponding distal information in both the virtual rendition of environments, and in the real environments. The environments we use here are Heb-Williams Mazes. These mazes entail a higher degree of complexity than most previous explorations of real-virtual transfer of spatial knowledge. Another important aspect potentially affecting previous results in this field has been the participant's level of visual experience. Here, we test the ability of several groups of participants with varying levels of visual experience ranging from congenitally blind participants through a group of people with late onset blindness and low vision to a group of blindfolded-sighted users and a sighted group navigating using vision.

Thus, in this study we answer the following questions: Are results from existing literature robust to more complex tasks? Are blind and blindfolded participants able to use the EyeCane and Virtual EyeCane to transfer spatial information between virtual and real environments? Are behavioral abilities similar across groups in both the real first and virtual first learning sequence of the environments?

II. Methods

A. Participants and Ethics (Heading 2)

Fifty six people participate in this experiment. Twenty-three sighted participants wearing blindfolds (15 women, range: 21-51 years, average: 28 years, mode: 24 years), thirteen additional sighted participants use vision to perform the tasks (8 women. range: 19-55 years, average: 28 years, mode: 21 years). Twelve congenitally blind (CB) participants (range: 23-59 years, average: 36 years, mode: 23 years), all with documented profound blindness from birth (except one participant before the age of 6 months). Eight participants with low vision (LV) or late acquired blindness (LB) (1 woman, range: 21-60 years, average: 40 years, mode: 21 years). Blindness is peripheral in all cases. Demographics of the blind participants are summarized in Table 1. All of the congenitally blind, low vision and late-blind participants are adept white cane users, and all participants have already taken part in a study involving the EyeCane [25] and have received one single day of training in a simple maze. For consistency all participants in the non-visual groups are blindfolded throughout the entire experiment. All fifty-six participants sign informed consent forms. This experiment is approved by the Hebrew University's ethics committee and conducted in accordance with the 1964 Helsinki Declaration.

TABLE I. Participant Characteristics

	Characteristics of Participants[a]					
Name	**Age**	**Sexe**	***Group***	***Onset***	**Light Perception**	**Cause of Blindness**
D.A.	59	M	CB	birth	None	ROP
M.D.	23	M	CB	birth	None	CG
U.M.	41	M	CB	6-7 months	None	ROP
O.B.	38	M	CB	birth	None	ROP
S.S.	54	M	CB	birth	None	ROP
O.G.	38	F	CB	birth	None	A
E.D.	33	M	CB	birth	None	ROP
E.H.	30	F	CB	birth	Very Faint	ROP
E.N.	30	F	CB	birth	None	A
M.S.	37	F	CB	birth	None	A
D.H.	35	F	CB	birth	None	ROP
B.J.	23	M	CB	birth	None	M
I.B.	33	F	LV	birth	Faint	G
M.Y.	21	M	LV	birth	Faint	RP
S.A.	21	M	LV	2-3 m	Faint	RP
S.B.	60	M	LV	birth	Faint	RP
V.G.	60	M	LV	birth	Faint	C
A.S.	27	M	LB	15 yrs	Faint	MA
H.A.	49	M	LB	43 yrs	None	MA
M.P.	54	M	LB	44 yrs	None	DR

a. **CB**: Congenitally Blind, **LV** : Low Vision, **LB**: Late Blind. **ROP:** Retinopathy of Prematurity. **M:** Months. **CG:** Congenital Glaucoma. **A:** Anophtalmia. **M:** Microphtalmia. **G:** Glaucoma. **RP:** Retinitis Pigmentosa. **C:** Craniosynostosis. **MA:** Medical Accident. **DR:** Diabetic Retinopathy.

B. The EyeCane and Real-World Mazes

The full technical details regarding the EyeCane (see Figure 1A) can be found in several previous dedicated publications [24-25]. Briefly, the EyeCane utilizes a set of Infrared sensors to extract the distance to the object it is pointed at. It then converts the distance information into pulsating sounds. In this paradigm a high frequency of sounds indicates that the object is closer to the user, while a low frequency indicates an object that is further away. With minimal training (<5 minutes), participants learn to interpret the frequency of pulsating sounds as accurate distances. The experimental environment consisted of Hebb-Williams mazes [26], which we constructed in a flexible manner [25] enabling us to change the configuration of the maze to test different spatial layouts. In this study, we use two different Hebb-Williams maze configurations (see Figure 2A, & B) in this experiment. These two mazes are equivalent in terms of complexity (number of segments, turns and decision points; see Shore [27] for a classification of Hebb-Williams mazes in terms of level of difficulty).

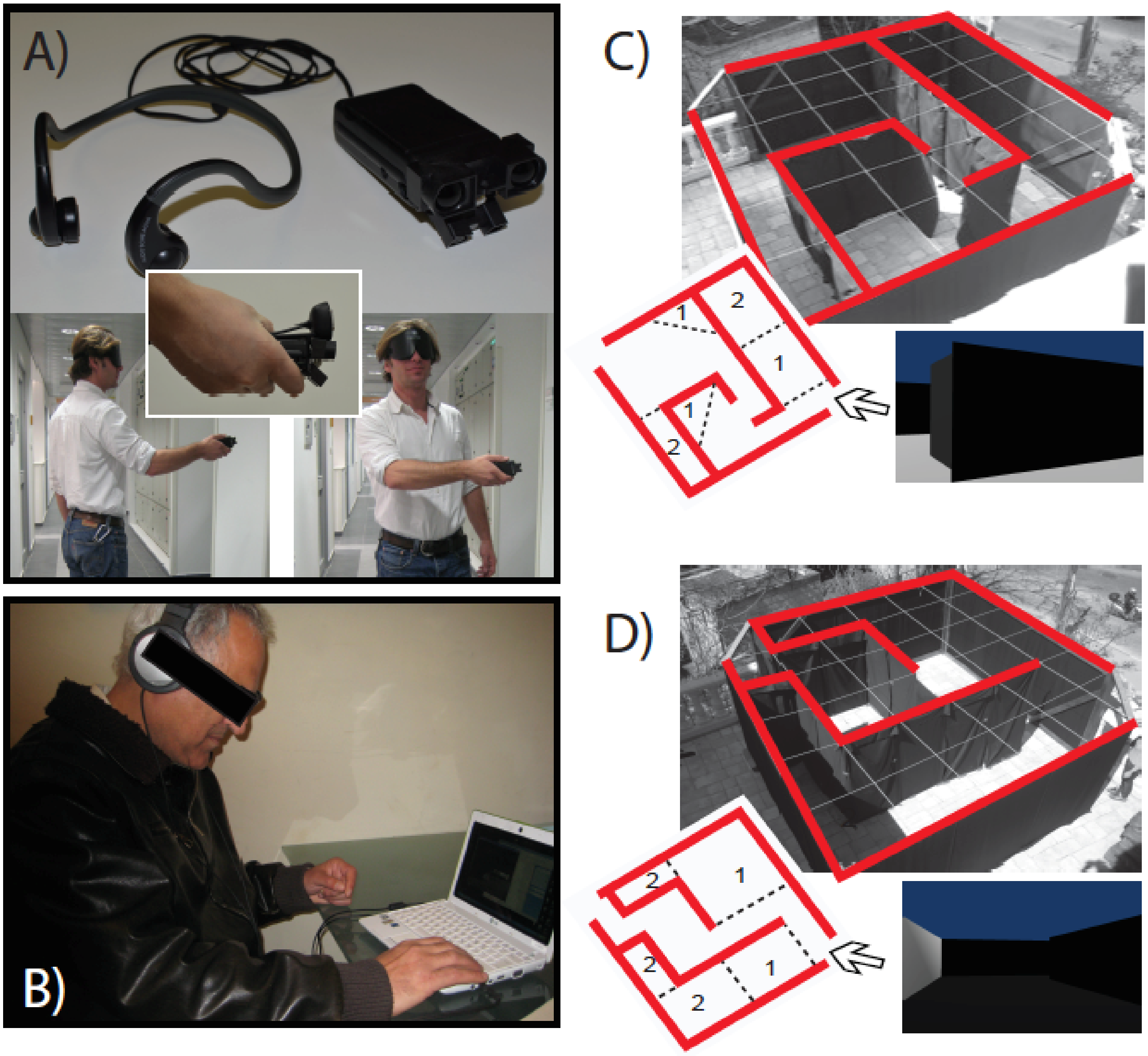

Fig. 1. *The EyeCane, Virtual EyeCane set-up and Mazes*. A. A top view, side view and closeup of the EyeCane and the IR sensors that capture the distanceto the object it is pointed at. B. A participant navigating a maze using the Virtual EyeCane. C. A real picture of maze A, a diagram showing error zones (dotted lines) and a first person view of the virtual rendition of maze A. D. A real picture of maze B, a diagram showing error zones (dotted lines) and a first person view of the virtual rendition of maze B.

C. The Virtual EyeCane and Virtual-World Mazes

Full technical details about the Virtual EyeCane (see Figure 1B) can be found in a previous demonstration of the use of the virtual EyeCane for simple environments and tasks [18, 23]. Briefly, our virtual mazes (Figure 1C and D) are created with Blender 2.49 and Blender-Python modules using python 2.6.2. The location and orientation of the user's avatar is tracked at all times at a rate of 60 Hz (identical to the rate of logic-ticks in the virtual environment, thus covering any possible in-game activity) to enable recreating and analyzing the participants' errors, contacts and time. The environments have a graphical output to the screen (see Figure 1B, C and D), which is used by the experimenter to track the participants' progress: the participants always experience the environments in the first person and not as a map overview. Distances within the environment are set so that each virtual meter corresponded to a real world meter. The virtual mazes are identical to the real world mazes, and the output from the Virtual-EyeCane at one virtual meter is the same as the sound output from the real-world EyeCane at a distance of one real meter.

D. Experimental Procedures

For both real and virtual mazes, all participants in the non-visual groups are blindfolded for homogeneity purposes. In the real world task, participants stand at the entrance of the maze and hold the EyeCane in order to scan the environment while wearing a pair of headphones that transmit the distance information based on the low/high sound frequency. In the virtual task participants are comfortably seated in front of a computer and received the distance information from a pair of identical headphones, based on the same low/high sound frequency, and navigate with the help of the arrow keys of a keyboard. Before beginning the task, participants are informed of the mapping between the auditory cues and distances: e.g. that a high frequency of sound means a nearby wall, a low frequency sound means a further away wall, and the absence of sound means that the passage is clear. They are instructed that their task is to find the fastest route to the exit while avoiding contacts (touching) with the walls. Participants are instructed to use the sounds of the EyeCane (or Virtual-EyeCane in the virtual environment) to scan the environment and to build a mental image of the maze. An error point is added every time a participant enters an error zone, or turns around towards the entrance instead of walking towards the exit. Contacts are counted every time a participant touches or made any contact with a wall, and an additional contact is recorded at every step if the participant continues contact with the wall . Time is measured from the moment the participants enters the maze until they exit the maze. Each real-world trial is video-recorded and can be viewed as often as necessary in order to accurately verify errors, contacts and time, and were also recorded by the experimenter during trials. Each virtual trial is both saved as a log file and also recorded manually by the experimenter. Over the course of two days, we systematically alternate the order of the mazes A & B (see Figure 2A & B) for both real-to-virtual and virtual-to-real sequences (see Table 2). In the real-to-virtual sequence participants first enter the real maze and used the EyeCane to scan the environment and find the exit. Their task is to complete the real maze five times in the real world. Then, they are immediately seated in front of a computer, and navigate while receiving the stimulation from the Virtual-EyeCane, potentially utilizing the spatial knowledge about the environment and the correct path through it that they had just previously learned in the real maze. As in the real maze, they complete the maze a series of five times. In the virtual-to-real sequence, the sequence is reversed: all participants are seated in front of a computer and navigate by receiving the stimulation from the Virtual-EyeCane. They then navigate the same maze a series of five times with the EyeCane, also potentially using their virtual experience.

E. Statistical Analysis

All analysis reported bellow are standard two-tailed T-tests, corrected for multiple comparisons via FDR (q=0.05, updated threshold at p<0.016). For each group we compare the first trial in one environment (real/virtual) to the second trial after exposure in the opposite sequence (virtual/real).

TABLE II. SEQUENCE OF MAZES

Day 1			***Day 2***		
Real First	Real Maze A	Virtual Maze A	Virtua l First	Virtual Maze B	Real Maze B
	Real Maze B	Virtual Maze B		Virtual Maze A	Real Maze A
Virtual First	Virtual Maze A	Real Maze A	Real First	Real Maze B	Virtual Maze B
	Virtual Maze B	Real Maze B		Real Maze A	Virtual Maze A

F. Low Vision and Late Blind Participants

This group of participants includes all participants with low vision and late-acquired blindness as an interim level between sighted-blindfolded who had full visual experience and congenitally blind who had none. In all cases, vision is either lost completely or severely impaired. Some with late onset complete blindness, and others with late onset visual impairments. Thus this group is less homogenous then the others in terms of visual experience. However, their behavioral performance and variance were similar to that displayed by the other groups. Note that similarly to the other groups navigating non-visually, all participants in this group are also blindfolded preventing the use of residual vision by the participants who were only severely visually impaired.

III. RESULTS

All groups show an ability to transfer their experience and spatial knowledge of the mazes in both directions between the real and virtual environments. Overall, participants show significant improvement in their amount of accrued errors, and minimal non-significant effects on contacts and time with high variance between groups.

A. Sighted Blindfolded.

The sighted-blindfolded group of participants improve their virtual world performance significantly in terms of errors following real world experience with the same maze (88% improvement, p<0.008), and even more so vice versa (253% improvement, p<0.0002). Virtual behavior improves also in terms of time and contacts but does not survive multiple comparisons. Real behavior does not improve in terms of time and contact.

B. Low Vision and Late Blind.

The group of low-vision and late blind participants improve their real performance in all parameters but none reaches significance. Their virtual performance improves significantly in terms of errors (242% improvement, p<0.00003), but only non-significantly in terms of contacts and time.

C. Congenitally Blind.

The group of congenitally blind participants improves significantly in terms of errors both in virtual (131% improvement, p<0.007) and real (128% improvement, p<0.003) environments. Virtual behavior improves, but not significantly, for time. Real behavior improves significantly after virtual training also for time (113% improvement, p<0.003) and contacts (100% improvement, p<0.009).

D. Sighted Full Vision

Sighted participants do not show significant improvement in any of the parameters in either direction, however their absolute scores are better than the rest of the groups.

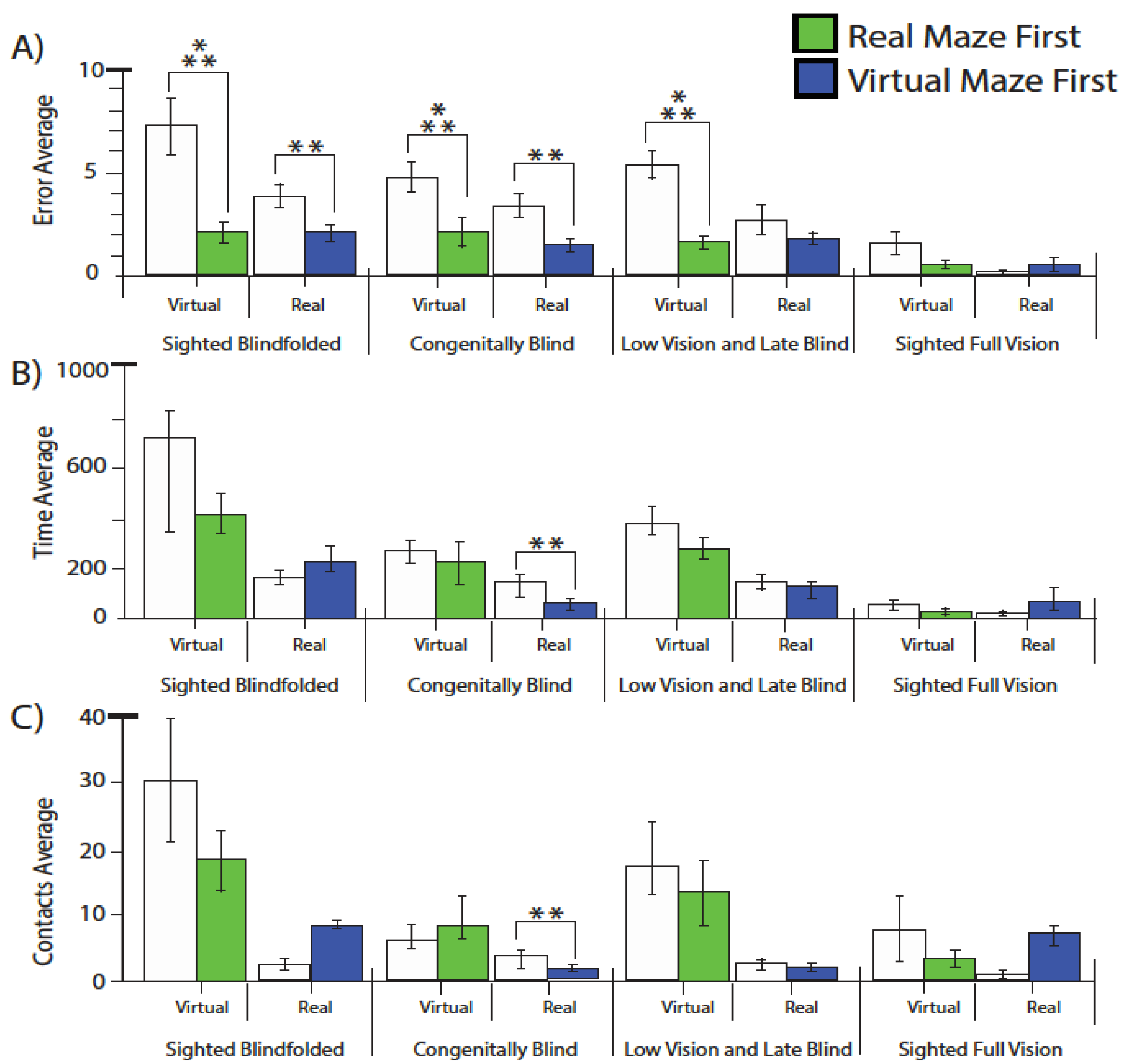

Fig. 2. *Transfer of Spatial Information between Real and Virtual Environments*. Behavioral results of our sighted blindfolded control (SbfC), congenitally blind (CB), low vision and late blind (LvLb) and sighted full vision control (SfvC) groups in terms of errors, time and contacts. White columns indicate no prior experience of the maze. Green columns indicate prior real experience of the maze. Blue columns indicate prior virtual experience in the maze. *p<0.05; **p<0.01; ***p0.001. A. Error Averages for all participants in the virtual and real mazes. B. Time averages for all participants in the real and virtual mazes. C. Contact averages for all participants in the virtual and real mazes.

IV. DISCUSSION

We explore the transfer of spatial information acquired non-visually from real to virtual and virtual to real environments, with emphasis on the impact of visual experience and on relatively complex environments, and on potentially boosting transfer with identical perceptual input.

We find that all participants can transfer spatial knowledge between environments. We find an improvement in errors when comparing performance with and without previous experience in the other type of environment (real/virtual). In general this effect is more pronounced in the real-to-virtual sequence, participants perform better in the virtual maze after having had experience in the real maze. However, the other performance parameters such as time and contacts do not improve significantly, and in some cases, even worsen.

While our results are similar across groups some differences emerge. The sighted group does not display strong learning effects and their performance is superior to the rest of the groups. It is quite possible that our sighted participants reach peak performance in these environments, which would explain why we do not see an improvement in performance. Participants navigating without vision perform worse in terms of errors, time and contacts, but their performance is still comparable to that of sighted participants using their full visual capacities. In a previous study using the EyeCane and Virtual EyeCane to navigate real and virtual mazes, we demonstrate that with training performance of blind and blindfolded participants was not significantly different from that of sighted participants [25]. In this study, we show that all non-visual groups can transfer spatial information between real and virtual environments in order to improve the number of errors they make.

A possible limiting factors of this study is the relatively small number of participants with limited visual experience. This group is actually composed of people with many different forms of visual experience, and it would have been interesting to be able to recruit more participants with low vision and late acquired blindness to separate these two groups. This would have enabled us to understand how different types of limited visual experience can affect the transfer of spatial knowledge between virtual and real environments. Furthermore, it is noteworthy that all of our participants are blindfolded for homogeneity purposes and that our results would be different had we allowed people of this group to make use of their remaining visual capacities. This is necessary however in order to test transfer of non-visual spatial information through the use of the Virtual EyeCane and EyeCane. Future studies should emphasize the different abilities of each sub-group and enable them to use their preferred strategy (making use of their remaining visual perceptual abilities for example in the case of low vision participants) when using SSDs to learn a new environment.

Our results suggest that it is possible to acquire spatial knowledge from different learning experiences, either from virtual reality training, or from a real world experience, and apply that spatial knowledge to a different rendition of the same environment. Among the non-visual groups, the congenitally blind group shows stronger learning effects than the blindfolded, consistent with more experience in non-visual navigation, or with an enhanced ability to use sensory substitution devices [18, 28, 29, 30; for review see: 31].

Richardson [32] finds that sighted participants use similar mechanisms when learning a real environment vs. a virtual reality one. Using visual cues in both virtual reality and real paradigms enables sighted participants to easily transfer information between representations. Our results suggest that this is also true for people with limited, or without any visual experience using sensory substitution to receive similar cues coding for distance in both real and virtual environments.

Seki & Sato [33] suggest that virtual training can help reduce ''veering'', which is walking off the path of the route, more than real training, and can reduce the stress of navigating a new route as much as real training for blind people. We show that not only is this training effective, but people without visual experience can benefit from virtual reality training to learn a route when using sensory substitution and reduce errors. This reduction of errors implies the reduction of the angularity effect, our participants were able to accurately represent distances and reduce errors after exposure to an environment through a different representation (real/virtual). Our results further suggest that orientation and mobility programs that seek to integrate virtual reality training for people who are blind [34-35] have great potential, and should also consider augmenting this training with the use of sensory substitution. Recent studies in virtual reality environments have demonstrated that the presence of visual reference frames significantly improves performance of participants to learn an environments [36]. For people who are blind, sensory substitution may help anchor reference frames to help translate spatial knowledge between real and virtual environments.

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