Effect of unconstrained walking plane with virtual environment on spatial learning: an exploratory study

Kanubhai K. Patel, *Ahmedabad University, Ahmedabad, India*
Sanjay K. Vij, *Sardar Vallabhbhai Patel Institute of Technology, Gujarat, India*

ABSTRACT. We have integrated the treadmill-style locomotion interface, called the unconstrained walking plane (UWP), with virtual environment (VE) to enable non-visual spatial learning (NSL). This setting allows for a new type of experience, whereby participants with visual disability can explore VE for NSL and to develop cognitive maps of it. Although audio and haptic interface has been studied for NSL, nothing is known about the use of locomotion interface for supporting NSL. We report an experiment that investigates the efficacy of UWP for NSL, formation of cognitive maps, and thereby enhancing the mobility skill of visual impaired people (VIP). Two groups of participants - blind-folded sighted, and blind - learned spatial layout in VE. They used two exploration modes: guided (training phase) and unguided (testing phase). In unguided exploration mode, spatial layout knowledge was assessed by asking participants to perform object localization task and target-object task. Results reveal that the participants have benefited by the learning, i.e. there were significant improvements in post-training navigation performance of the participants.

KEYWORDS: *Cognitive maps, Locomotion interface, Spatial learning, Virtual environment, Visual impairment*

Unlike in case of sighted people, spatial information is not fully available to visually impaired people (VIP) causing difficulties in their mobility in new and unfamiliar locations. As they are handicapped to gather this crucial information, they face great difficulties in generating efficient mental maps of spaces and, therefore, in navigating efficiently in new and unfamiliar spaces. Consequently,

many VIP become passive, depending on others for assistance. More than 30% of the VIP does not ambulate independently outdoors (Clark-Carter et al., 1986; Lahav, Mioduser, 2003). This constraint can be overcome by providing mental mapping of spaces, and of the possible paths for navigating through these spaces which are essential for the development of efficient mobility skills. Such assistance might not be required after a reasonable number of repeated visits to the new space as these visits enable formation of mental map of the new space subconsciously. Thus, a good number of researchers focused on using technology to simulate visits to a new space for cognitive maps formation. Although isolated solutions have been attempted, no integrated solution of non-visual spatial learning (NSL) to VIP is available to the best of our knowledge. Also most of the simulated environments are far away from reality and the challenge in this approach is to create a near real-life experience.
Virtual Environment (VE) creates the illusion of participation in a synthetic environment rather than going through external observation of such an environment (Earnshaw et al., 1993).

Figure 1. Spatial learning by VE exploration using UWP

Essentially, VE allows users to interact with a simulated environment. Users can interact with a virtual environment either through the use of standard input devices such as a keyboard and mouse, or through multimodal devices such as a wired glove, the Polhemus boom arm, or else omni-directional treadmill.
We provided omni-directional UWP (as shown in Figure 1) based

on treadmill as a locomotion interface to the VE to acquire spatial knowledge and thereby to structure spatial cognitive maps of an area. VE is used to provide spatial information to the VIP and prepare them for independent travel. The locomotion interface is used to simulate walking from one location to another location. The device is of a limited size that allows a user to walk on it and provide a sensation as if he is walking on an unconstrained plane.

The purpose of the current study is to evaluate the efficacy of the UWP for NSL which leads to enhancement of the mobility skills of VIP. The main research questions of this study are as follows:

1) Does VE exploration using UWP contribute to the construction of a cognitive map of the unknown space which enhances the mobility skill of VIP?
2) Does VE exploration using UWP contribute to communicate the spatial knowledge and thereby to localize the landmarks of the unknown space?
3) Does UWP provide overall satisfaction with natural walking, full immersion, enjoyment and secure way to walk?

These research questions lead to the following hypothesis, which were explored during the research study.

1) Participants can create cognitive maps of an area, localize the landmarks and there is significant improvement in navigation performance of the blind participants after getting training on our system. We hypothesized that participants have benefited by the training, i.e. post-training navigation performance of the participants is same as of pre-training navigation performance.
2) Users of all types of participants (i.e. blind-folded sighted and blind) performed object-localization task equally. This hypothesis will help us to determine whether type of blindness influences spatial learning or not.
3) Participants strongly agree that UWP provides overall satisfaction for spatial learning. UWP provides a possibility for the blind user to perform natural walking with full immersion and realism. The rationale for our expectations was that UWP may lead to complete perceptual and reduced memory processing that is likely to result in reduction in the

demand on learning layouts without visual information.

The remaining paper is structured as follows: Section 2 presents the review of related literature. Section 3 describes planning and procedure for experiments. Section 4 illustrates the results. Section 5 concludes the paper and presents the limitations of device.

Review of related literature

Spatial learning

In recent years, a plethora of assistive navigation technologies have been designed to enhance and maintain the independence of the community of visually impaired. VE has been a popular paradigm in simulation-based training, game and entertainment industries (Burdea, Coiffet, 2003). It has also been used for rehabilitation and learning environments for people with disabilities (e.g., physical, mental, and learning disabilities) (Standen et al., 2001; Schultheis, Rizzo, 2001). Recent technological advances, particularly in haptic interface technology, enable blind individuals to expand their knowledge as a result of using artificially made reality through haptic and audio feedback. Research on the use of haptic devices by people who are blind for construction of cognitive maps includes (Lahav, Mioduser, 2003; Semwal, Evans-Kamp, 2000). The use of audio interface by VIP for construction of cognitive maps includes Audio-Tactile BATS (Parente, Bishop, 2003); modeling audio-based virtual environments for children with visual disabilities (Sanchez, Baloian, 2005). The use of audio-haptics interface by VIP for construction of cognitive maps includes haptics and vocal navigation software (Virtual Sea - for blind sailors) (Simonnet et al., 2006); Haptics Soundscapes team (Rice et al., 2005). Although audio and haptic interface has been studied for NSL, nothing is known about the use of locomotion interface for supporting NSL.

Locomotion interface

Good number of devices has been developed over the last two decades to integrate locomotion interfaces with VE. We have categorized the most common VE locomotion approaches as follow:

- Treadmill-style interface (De Luca et al., 2007; Iwata, Yoshida,

1999; Hollerbarch et al., 2000; Darken et al., 1997)
- Pedaling devices (such as bicycles or unicycles) (Iwata, Fuji, 1996)
- Walking-in-place devices (Sibert et al., 2004)
- The motion foot pad (Iwata et al., 2005)
- Actuated shoes (Iwata et al., 2006)
- The string walker (Iwata et al., 2007)
- Finger walking-in-place devices (Kim et al., 2008)

Generally, a locomotion interface should cancel the user's self motion in a place to allow the user to go to anywhere in a large virtual space on foot. For example, a treadmill can cancel the user's motion by moving its belt in the opposite direction. Its main advantage is that it does not require a user to wear any kind of devices as required in some other locomotion devices.

Planning and procedure for experiment

The experiment was conducted to examine whether the participants were able to create cognitive maps of so-called survey-map type by exploring the VE, and to evaluate the practical effectiveness of this newly developed aid.

Participants

Fourteen volunteers recruited as test participants for this research. All participants were between the ages 17 and 35 and unknown about place, have self-reported normal spatial learning. They were divided in to two groups - bind-folded sighted (8 participants) and blind (five congenital blinds and one late blind) - learned to form the cognitive maps from a VE exploration.

Experimental apparatus

We developed UWP for VE exploration. The mechanical structure of UWP is shown in Figure 2. It consists of a motor-less treadmill resting on a mechanical rotating base.
The experimental software is run on a laptop-based system with a 2 GHz Intel Core 2 Duo processor, 2 GB RAM and a 15" monitor. It is developed in Java language using the JDK 1.5 API.

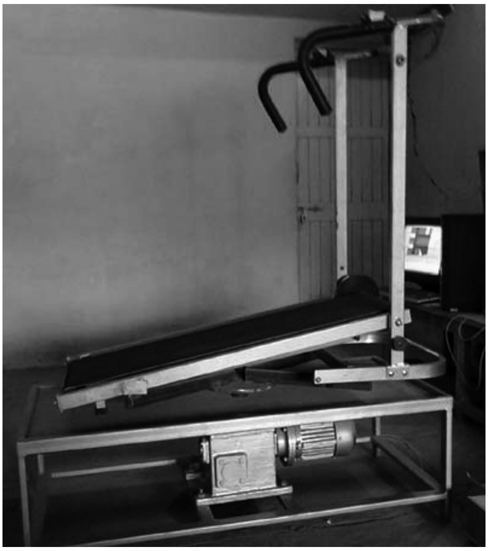


Figure 2. Mechanical structure of UWP

We developed computer-simulated virtual environment based on ground floor of our institute (as shown in Figure 3), which has three corridors and eight landmarks. It has one main entrance. The system lets the participant to form cognitive maps of unknown areas by exploring VE using UWP (as shown in Figure 1). It can be considered an application of "learning-by-exploring" principle for acquisition of spatial knowledge and thereby formation of cognitive maps using VE. It guides the VIP through speech by describing surroundings, guiding directions, and giving early information of a turning, crossings, etc. Additionally, occurrences of various events (e.g. arrival of a junction, arrival of object(s) of interest, etc.) are signaled by sound through speakers or headphones.

Research instruments

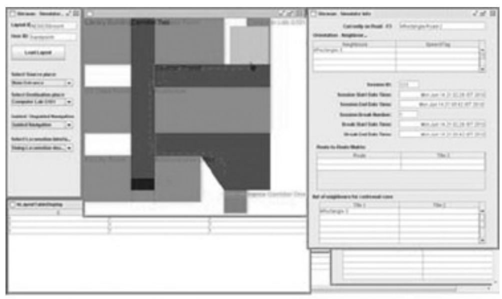
Nine main instruments served the study; the last five instruments were developed for the collection of quantitative and qualitative data. The research instruments were:

1) The Unknown Target Space - The space to be explored as a virtual space in the VE (see Figure 3). It is a 230-square-foot building with one entrance, eight landmarks and three corridors.
2) Exploration Task - Each participant was asked individually

to explore the virtual building and to complete the given task. The task was repeated four times, taking maximum five minutes for each trial. The experimenters informed the subjects that they would be asked a) to describe the building and its components, b) to locate five landmarks as asked by the experimenter, and c) to perform target-object task at the end of their exploration.

3) Object-localization task - Participants were asked to locate particular five objects in a fifth trial of navigation (with in five minutes). In this trial participants were provided contextual help only. In case of confusion, participant may get help from system by paying penalty for it. Same way, in case of mistake made by participants, system warns them and provides help.

Figure 3. Screen shot of Computer-simulated environments



4) Target-object Task - In the last trial, participants were asked to perform target-object task that is "to go to computer lab starting from main Entrance". Participants were asked to perform this task using contextual help only. In case of confusion, participant may get help from system by paying penalty for it.
   Same way, in case of mistake made by participants, system warns them.
5) Questionnaire - The questionnaire comprised of 8 questions concerning the participants' views and feedback about the UWP and system. The participants were given this questionnaire at the end of last trial.
6) Interview - The participants were asked to give verbal description of the unknown environment. Participants were asked about their experience and views about the study.
7) Observations - For recording the participant's exploration,

we used video camera of cell phone. Their navigation process and audio remarks in the VE were recorded during the tasks. The information from these recordings was combined with the computer log recording.

8) Computer Log - The log enabled the researcher to analyze users' learning and exploration process in the VE, as regards to their distances traversed, duration taken, and breaks.
9) Evaluation Schemes - It served the researcher's analysis of the participants' mobility skills and their acquaintance process with the new space.

Procedure

All participants carried out the specified tasks and were observed individually. The study was carried out in five stages: (i) familiarization with the VE features and operation of the UWP; (ii) participants' exploration of the unknown virtual space using the UWP; (iii) performing object-localization task (the participants were asked to locate five landmarks as asked by the experimenter); (iv) participants were asked to perform the Target-object task (the user were asked to go to particular landmark); (v) participants were asked to answer questionnaire and give a verbal description of the environment. In the last four stages, i.e. (ii) to (v), all participants' performances were video-recorded.
In first stage, i.e. familiarization stage, participants spent a few minutes using the system in a simple virtual environment. The duration of such practice session was typically about 3 minutes. It helped the participants to familiarize themselves with the UWP and the system, before the trials began. The goal of this stage was not to give enough time to participants to achieve competence.
After the familiarization stage, the following three tasks were given to participants:

1) Exploration task
   Participants were asked to explore the VE and to complete the given task. Each participant repeated the task four times, taking maximum five minutes for each trial. Participants navigated the virtual space using first mode of navigation, i.e. they were provided the contextual cues and system help both.
2) Object-localization task

The participants were asked to locate five landmarks as asked by the experimenter. This task took a maximum of five minutes. Participants navigated the virtual space using second mode of navigation, i.e. without system help. In case of confusion, participant may get help from system by paying penalty for it. Same way, in case of mistake made by participants, system warns them.

3) Target-object task
   The participants were asked to complete following task, i.e. "Go to the Computer Laboratory starting from Main Entrance". The time allotted for this task was maximum 5 minutes. Participants navigated the virtual space using second mode of navigation, i.e. without system help. In case of confusion, participant may get help from system by paying penalty for it. Same way, in case of mistake made by participants, system warns them.

Statistical analysis

The independent variables used for the analysis included (i) trial number, (ii) mode of virtual navigation, and (iii) the type of participants (blind-folded sighted and blind). The dependent variables were categorized into two categories:

a) Number of objects located and identified correctly, and
b) (i) time taken, (ii) number of times help taken, (iii) number of times help provided, and (iv) number of pauses taken to complete the task of traversing 350-feet length of specified route. A t-test was used to analyze the experimental data with a level of significance (α) taken as 0.05. The feedback from the participants was also analyzed using t-test.

Results

Hypothesis 1:

Ho: The participants have not benefited by the training, i.e. post-training navigation performance of the participants is same as of pre-training navigation performance.
Ha: The participants have benefited by the training, i.e. there is significant difference in post-training navigation performance and pre-training navigation performance of the user.

We claimed that spatial learning with our system can greatly enhance the navigation performance and mobility skills of participants. The VE exploration using UWP contributes to the construction of a cognitive map of the unknown space which enhances the mobility skill of blind.

Table 1. Pre-training/Post-training mean scores in spatial learning performance

Parti.	Variables	Pre-training		Post-training	P<0.05
		Mean	SD	Mean	SD
BFS (8 in No.)	Time taken (in minutes)	2.91	0.43	1.91	0.21
	Number of times help taken	6.88	0.64	1.87	0.52
	Number of times help provided	7.38	0.52	1.75	0.46
	Number of times pauses	6.88	0.35	2.25	0.46
BL (6 in No.)	Time taken (in minutes)	3.07	0.39	2.17	0.12
	Number of times help taken	6.83	0.75	1.83	0.41
	Number of times help provided	7.00	0.63	1.33	0.52
	Number of times pauses	6.50	0.55	2.00	0.52

Significant improvements were found in the post-training trial as compare to the pre-training trial concerning the characteristics of the exploration process. These differences are related to three variables: the total duration of the exploration, the number of times helps taken, the number of times helps provided and the number of pauses made while exploring the unknown space. Data in Table 1 show significant differences between the pre-training trial and the post-training trial in that participants during the pre-training trial took more number of helps and pauses during their exploration tasks. To analyze the statistical significance of post-training gains, the paired samples t-test was used.

Significant post-training difference was found (i) T7 = 5.95, $p<0.05$ and (ii) T5 = 5.32, $p<0.05$ for the factor of time taken to complete the task. Here calculated value is more than table value, so null hypothesis is rejected. We can say that the participants have benefited by the training, i.e. there is significant difference in post-training navigation performance and pre-training navigation performance of the user. It is possible to think that the UWP is the key factor for the improvement in the scores.

Hypothesis 2:

Ho: Participants of all types of participants performed object-localization task equally.

Ha: Performance for object-localization task is not same by all types of participants.

Table 2. Mean scores during object-localization task

	BFS	BL
Mean	4.50	4.33
SD	0.75	0.81
N	8	6

The VE exploration using UWP contributes to communicate the spatial knowledge equally to participants of all types of blindness and thereby they can locate the landmarks of the unknown space equally.

As per t-test, there is a 95% confidence level (5% significance level) that population mean will range between 3.90 (i.e., 4 landmarks) to 5.09 (i.e., 5 landmarks) for BFS and between 3.61 (i.e., 4 landmarks) to 5.05 (i.e., 5 landmarks) for BL.

The calculated value (T13=0.394, $p<0.05$) is less than table value, so it is possible to think that there is no significant difference between the BFS and the BL group concerning the characteristics of the landmark localization process. Irrespective of the type of participants, the system provided the same possibility for a user to recognize or localize the landmarks correctly.

Hypothesis 3:

Ho: Participants strongly agree that UWP provides overall satisfaction for non-visual spatial learning.
Ha: Participants strongly disagree that UWP provides overall satisfaction for non-visual spatial learning.

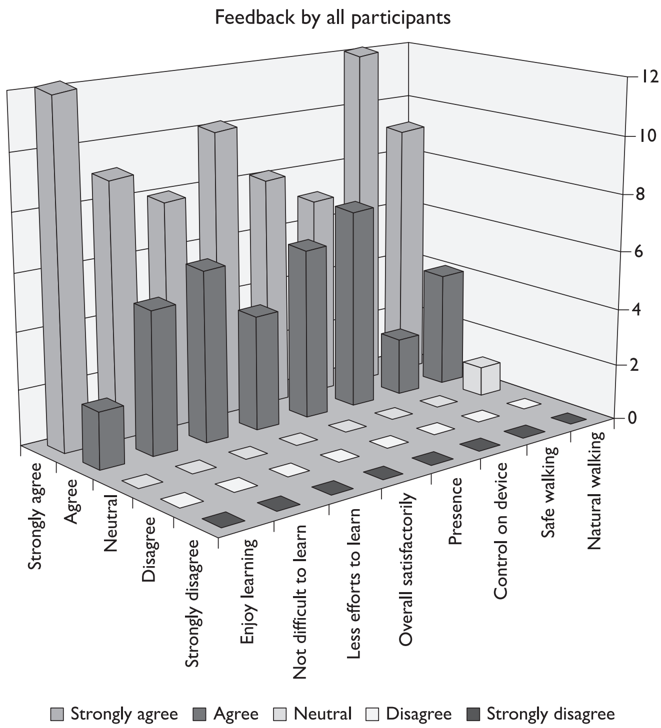


Figure 4. Participants feedback

As per t-test, there is a 95% confidence level (5% significance level) that population mean will range between 4.22 (i.e., 4 rank of agree) to 5.03 (i.e., 5 rank of strongly agree) for BFS and between 4.44 (i.e., 4 rank of agree) to 5.22 (i.e., 5 rank of agree) for BL.
The calculated t-value is less than table value, so it is possible to think that the all participants strongly agree that UWP provides overall satisfaction for NSL. The result proved that our novel UWP is effective for NSL by VIP to perform natural walking with full immersion and realism.

General comments and feedback

The kind of general comments and feedback received from the participants is given below:

"The virtual movements did not become natural until 3-4 trials".
"The exploration got easier progressively each time".
"I found it somewhat difficult to explore. As I explored, I got better".

Although there was a general satisfaction among the participants, there were some comments indicating a scope for further improvements in the device. Such comments are given below:

"I had difficulty making immediate turns in the virtual environment".
"Virtual walking through keyboard needs more efforts than real walking".

Conclusion

We have integrated the novel treadmill-style locomotion interface - unconstrained walking plane (UWP) - with virtual environment (VE) to enable non-visual spatial learning (NSL). UWP allows user to navigate in VE as they walk on the device. The motivation to use UWP was driven by its potential to provide near-natural feeling of real walking leading to NSL and effective development of cognitive maps for unknown locations. Results reveal that the participants have benefited by the training, i.e. there were significant improvements in post-training navigation performance of the participants.
The experimental results and participants' feedback have conclusively indicated that the UWP is very effective for independent NSL and thereby enhancement of mobility skills of VIP. Its simplicity of design coupled with supervised multi-modal training facility makes it an effective device for virtual walking simulation and thereby for NSL. The results match with our expectations that UWP would result in complete perceptual and reduced memory processing that considerably reduces demand on learning spatial layouts without visual information. One known

limitation of our device is its inability to simulate movements on slopes and highly zigzag paths

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Sintesi

La locuzione "perdere l'orientamento" rientra nei modi di dire comuni: è tuttavia evidente che assuma significati differenti a seconda di chi utilizzi questa espressione. Per un vedente significa perdere la direzione, non riuscire a trovare i riferimenti visivi utili e riconoscibili per rendere individuabile un luogo; sarà sufficiente leggere una targa toponomastica o riconoscere un oggetto inserito nell'ambiente o, ancora più genericamente, le caratteristiche geografiche dell'ambiente stesso o paesaggistiche circostanti.

Per il non vedente, questo semplice modo di dire, assume un significato più complesso: egli dapprima deve individuare il suo orientamento spaziale; in subordine potrà trovare la propria strada; quindi gli sarà necessario raccogliere diverse e cruciali informazioni reperibili dagli altri sensi (quali: suoni e rumori, profumi e odori, disconnessioni o meno del terreno, ecc.) che gli serviranno per generare delle mappe mentali, efficienti tanto da permettergli di muoversi in spazi nuovi e poco conosciuti.

Spesso però questa raccolta di informazioni fa sì che molti non vedenti e/o ipovedenti diventino passivi, perché costretti a dipendere dagli altri per l'assistenza. Più del 30% dei non vedenti e/o ipovedenti non si muovono da soli all'aperto.

La tecnologia ha un ruolo molto importante per il miglioramento della vita di

questa categoria di disabili. Orientamento e wayfinding - i motori della creazione della mappa mentale da parte di un non vedente e/o ipovedente - sono i cardini di uno studio che ha cercato di risolvere i problemi che insorgono nell'approccio quotidiano della psicologia cognitiva e percettiva del disabile visivo nel contesto urbano durante la deambulazione, mediante la percezione extra-visiva. Assumono pertanto primaria importanza le informazioni di natura acustica, tattile, igrotermica, olfattiva, cinestetica, ecc., emesse dall'ambiente: elementi che rientrano nella recettività del non vedente, quindi interpretabili dall'attività cognitiva rivolta alla componente dinamica del wayfinding.

Un buon numero di ricercatori si sono concentrati sull'utilizzo di tecnologie atte a simulare le visite in uno spazio non conosciuto per studiare la formazione di mappe cognitive. La maggior parte degli ambienti simulati sono lontani dalla realtà e la sfida dei ricercatori è, oggi, quella di creare una esperienza di vita quasi reale.

Virtual Environment crea l'illusione di far parte di un ambiente del tutto simile alla realtà consentendo agli utenti di interagire con l'ambiente simulato attraverso l'uso di dispositivi di input standard, quindi come una tastiera e un mouse, o attraverso dispositivi multimodali come un guanto cablato, il braccetto Polhemus, tapis roulant (interfaccia di locomozione usato per simulare a piedi lo spostamento da una posizione ad un'altra).

Dallo studio è emerso che i partecipanti sono stati in grado di creare mappe cognitive di un territorio, localizzando i punti di riferimento. Il miglioramento delle prestazioni di mobilità, avvertito da chi ha utilizzato il sistema simulato, è risultato paragonabile alle prestazioni di coloro che hanno effettuato le ricognizioni in loco.