Use of virtual environments to acquire spatial understanding of real-world multi-level environments

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ABSTRACT

This article outlines experimental work investigating the way that people encode vertical as well as horizontal spatial information from exploration of virtual environments (VEs). We present two studies using simple multi level VEs that provide novel evidence for a vertical asymmetry in spatial memory, where downward spatial judgments are more accurate than upward spatial judgements. The effect was found in able-bodied adults and children, and in physically disabled children. A third study examined transfer of spatial learning from a VE to a real-world equivalent environment using a simulation of a multi-level complex shopping centre with elderly participants. This study confirms the potential of VEs as training media for the elderly.

1. INTRODUCTION

Numerous studies using VEs have demonstrated that spatial knowledge can be effectively acquired from virtual exploration alone, and that such information can be readily transferred to real equivalent environments (see Rose and Foreman, 1999, for a review). With a few exceptions (e.g. Wilson, Foreman, & Tlauka, 1997) most studies of transfer have been based on the horizontal plane, with movements (viewpoint shifts) within the virtual world being restricted to left-right rotation/translation, and forward-back displacements. Most studies have used single storey buildings and subsequent tests of spatial competence have used measures based on way-finding or pointing to obscured targets in the horizontal plane (e.g., Rose et al, 1999; Stanton et al, 1998).

Although many environments used by people with disabilities are constructed on only one level (for example, most special schools are just one storey buildings), in daily life children and adults encounter more complex buildings with many levels (office blocks, shopping centres, car parks), so it is important that spatial learning is not restricted to horizontal spatial relationships. In one of the few studies carried out using a multi-tiered building, Wilson et al (1997) found that, although people could point with some accuracy to objects on a different floor, performance was poorer than when pointing to objects on the same floor.

In a series of studies (Wilson, Foreman, Stanton and Duffy, submitted, a & b) we have examined both horizontal and vertical pointing judgements in a simplified 3-level environment containing multiple targets. We outline these studies and then describe a study investigating transfer of spatial information on both the horizontal and vertical plane in a real-world multi-level building following exploration of an equivalent simulation.

2. EXPERIMENT 1 - ADULTS VERTICAL ENCODING

Participants explored a VE consisting of 3 vertically aligned levels, connected by a lift and a staircase. Each room contained two target objects. Following a period of exploration, participants estimated the location up

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and across (tilt and rotation) of each object from two viewpoints on every floor in turn. None of the target objects were visible from their testing position (see Wilson, et al, submitted, a).

2.1 Participants

Twenty-seven able-bodied participants with a mean age of 25 years 2 months (range 18-53 years) took part in the study.

2.2 Materials

The experimental environment was developed using the Superscape Virtual Reality Toolkit and was presented on a desktop computer. The experimental environment consisted of three vertically aligned rooms, which formed a three-storey building. Each room was a different colour. The rooms were connected by a staircase on one side of the room and an open lift on the other side of the room. Six target objects were located within the environment, two in each room (see figure 1). The relative locations of the objects in the different rooms were counter-balanced across participants.

Following exploration, all the objects were removed from the environment. Six static viewpoints were created, with two viewpoints on each floor in the same relative locations. The cursor keys were used to control pointing using cross hairs in the centre of the screen. The left and right keys enabled rotation movements and the up and down keys enabled tilt movements. Tilt and rotation angles were displayed on an instrument panel at the side of the screen.

A practice environment consisted of an open green space in which a raised brown platform could be reached by lift or stairs. Two target objects were placed within the environment, one on the platform and one on the ground.

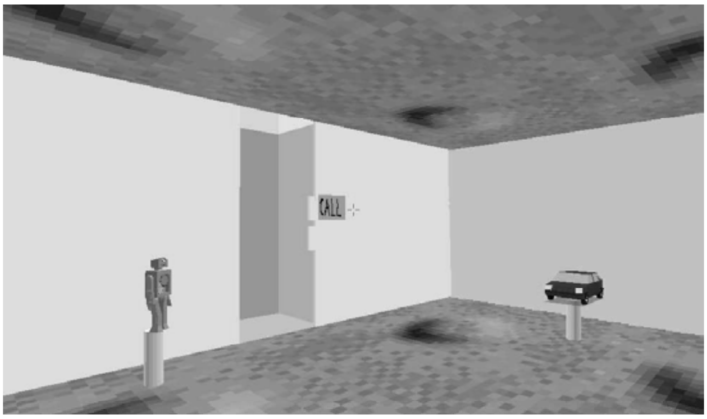

Figure 1. *One of the rooms in the 3-storey simulation containing two target objects*

2.3 Design and Procedure

Participants were tested individually. First they explored the practice environment and were asked to point to the two target objects, when obscured, to check that they understood the procedure and were familiar with controlling exploration. Then each participant was presented with the 3-storey experimental environment. Exploration started with a view in the middle room, from just in front of the lift facing towards the centre of the room. They were asked to explore all three rooms using the lift and stairs for as long as they wished, and to visit each room at least twice. They were told that the purpose of the exploration was to remember the location of the six objects.

When they were familiar with the objects and their locations, participants were asked to complete pointing tasks. They were told that they were looking at the same VE that they had explored, but with the objects removed. They were told that on some test trials they may need to point up through the ceiling or down through the floor to illustrate the former locations of some of these objects. All participants were tested at each of the six test locations, and from each location they were asked to point towards the former location of each of the six test objects in turn. Test locations and object order were counterbalanced. For each judgment, tilt and rotation angles were recorded (as well as time taken - see Wilson, et al, submitted, a).

2.4 Results and Discussion

Errors scores for the tilt and rotation judgements were calculated by subtracting the angles of the participants' estimate of the direction of the target objects from the actual angle. Overall, errors were lower than expected by chance on all judgements, but poorer performance was found when pointing to upper rather than lower floors. Analysis of the mean absolute tilt errors revealed a significant linear trend, F (1,26) = 11.41, MSE = 404.75; a planned comparison between upward and downward judgments revealed a significant difference, with less accurate upward than downward judgements F (1,56) = 10.71, MSE = 383.01 (*M*s 31 and 19° error respectively).

This is the first experiment to demonstrate that people have a bias in the accuracy of their spatial representations in the vertical dimension, favouring spatial arrays that are lower rather than higher than the horizontal plane.

3. EXPERIMENT 2 – CHILDRENS VERTICAL ENCODING

Experiment 1 found that the absolute tilt and rotation errors for adult participants who had explored a multi-storey VE revealed an asymmetry in participants' spatial representations, with more accurate judgements directed to lower rather than higher floors. The presence of asymmetry is particularly important when considering the potential of VE technology for people with disabilities who find it difficult to navigate through large multi-level buildings such as shopping centres and museums, and who might benefit from using a VE to orientate themselves and acquire information about building layouts and facility locations before visiting the real environment. Difficulty in accessing the built environment remains a major factor in limiting the mobility of disabled individuals (Foster, Wenn & Harwin, 1998) and thus educating spatially impaired individuals might in future represent a beneficial application of VE use. Yet large public buildings are typically confusing, specifically because they consist of multiple levels, and so it is important to know whether VEs can be used as a training medium in such situations.

As Stanton et al (in press) found that the effects of restricted mobility can persist from early childhood into adolescence; we tested a group of physically disabled children along with a group of able-bodied children in the same task (Wilson, et al, submitted, b). Our hypotheses were, first, that we might find evidence of vertical spatial asymmetry in children, suggesting that learning this bias occurs earlier than adulthood. Second, we suspected that there might be a difference in vertical orientation ability between able-bodied and physically disabled children due to their different experience of self-controlled exploration.

3.1 Participants

Two groups were recruited from local schools. One group consisted of 12 physically disabled children with a mean age of 8 years and 2 months (range: 5-10 years), of whom 10 were males. All of the physically disabled group had current mobility impairments and had experienced mobility difficulties since birth. Six participants used wheelchairs and the remainder were able to walk with the aid of a walking frame. The second group consisted of 19 able-bodied children with a mean age of 9 years and 5 months (range: 5-13 years), of whom 12 were male. *Materials* and *Design and Procedure* are as in Experiment 1.

3.2 Results and Discussion

The analysis of the absolute tilt errors revealed a similar pattern to the previous study, in which spatial judgements below the horizontal plane were more accurate than those above the horizontal plane. ANOVA analysis revealed a significant main effect of group, F (1, 27) = 6.32, MSE = 273.47, reflecting greater overall errors in the disabled group (*M*s = 37 and 31° error, for the disabled and able-bodied groups respectively), that occurred predominantly when estimating target objects 2-storeys up. This analysis also found a significant main effect of storey, F (2, 48) = 14.89, MSE = 552.93; no other main effects or interactions were significant (ps > .1). Planned comparisons on the combined upward versus the combined downward tilt errors found a significant difference, with greater errors for upward judgements, F (1. 65) = 8.07, MSE = 537.33 (*M*s 42 and 31° error respectively).

Thus, in both Experiments 1 and 2, absolute tilt errors revealed an asymmetry, with more accurate judgements directed to lower than higher floors, with a suggestion in Experiment 2 that this asymmetry was more pronounced in physically disabled than able-bodied children. Errors of the children overall were significantly higher than those of the adults in Experiment 1 (*M*s = 33, and 23° error respectively).

In summary, the results of these two experiments indicate that participants who explored a 3-storey VE were more accurate in making spatial judgements below the horizontal plane than above the horizontal plane. This is a novel finding which needs to be borne in mind when using VEs for training in multi-storey buildings.

4. EXPERIMENT 3 - TRANSFER OF SPATIAL SKILL FROM A SIMULATION TO AN EQUIVALENT REAL-WORLD SHOPPING CENTRE

If skills are learned in a virtual environment it is essential that they transfer to real environments for the experience to be of any real benefit. Although many measures have been developed in VE's, only a limited number of studies have demonstrated effective transfer of training (Linden et al., 2000; Mendozzi, Pugnetti, Barbieri et al, 2000; Rose, Brooks & Attree, 2000; Stanton et al., 2000).

It is of particular interest to know whether older individuals can make effective use of VE technology. In terms of spatial cognition, older individuals have had years of experience in acquiring and interpreting spatial information and of independent navigation in a wide range of environments. However, there are potential limitations to VE use by older individuals that do not apply to other groups. Older individuals may be slower and less dextrous when making motor responses and controlling displacements; their memory may be impaired, and they are less familiar with computers compared with younger age groups (Foreman Stanton, Wilson, Duffy & Parnell, submitted). McDonald et al (1999) found that a group aged around 70 years took twice as long as younger participants to navigate through doorways in a series of virtual rooms, yet they completed the task without difficulty. Rose et al (1999) found that stroke patients aged 25-85 years (mean: 61 years) with a wide range of motor and cognitive impairments, although not as good at acquiring information about building layouts as non-brain-injured controls, nevertheless showed significant spatial learning, particularly when actively directing their own virtual exploration.

In a third study we examine vertical and horizontal encoding using a VE modelled on a real multi level building. It has been suggested that as the population ages, senior citizens might be expected to make increasing use of VE training (McDonald et al, 1999). Since many of the environments that senior citizens may wish to visit, but feel reluctant to visit, are public buildings, the present study took the elderly as a user group and examined exploration in a complex VE public shopping mall, with retail outlets on two levels. Participants understanding of places and routes was then assessed in the real shopping mall. (For a detailed description of this study see Foreman, et al, submitted).

4.1 Participants

Thirty-two participants were recruited, of whom 16 had reached retirement age, and 16 were university undergraduates. None had prior experience of the shopping centre. Each age group was subdivided into 8 experimental and 8 controls. The younger groups' mean ages were 26.3 years (range: 21-33) in the experimental group, and 21.75 (range 17-35) in the control group, having 3 and 4 males respectively. The older groups' corresponding mean ages were 73.9 years (range: 62-82) and 74.6 years (range: 64-82), having 2 and 3 males respectively. All had normal or corrected-to-normal vision. All were physically mobile.

4.2 Materials

The VE was modelled using Superscape Virtual Reality Toolkit to scale, using the architects' plans. The environment consisted of a two-level shopping centre in Leicester containing over 60 retail outlets (see figure 2). Most outlets line the sides of a wide main concourse. Additionally there are alleyways at either end, also lined with shops, which lead from the concourse toward washroom facilities, restaurants and entrances/exits. At both ends of the shopping centre there is an escalator, stairway and a lift, which were used during exploration to move between floors. The interiors of shops could not be explored.

A hand-held metal pointer attached to two fixed 360^o protractors, in the vertical and horizontal planes, was used to point towards the target objects. Participants moved the pointer horizontally and vertically to indicate the horizontal direction and tilt angle of the centre of each target object.

4.3 Design and Procedure

Participants in the experimental group explored a simulation of the shopping centre on an individual basis over four days for approximately 30 minutes per day. During each session they explored the VE shopping centre in the presence of the experimenter who checked that they had explored the whole of the environment. During the final two sessions target locations that were to be used for testing in the real shopping centre were emphasised to participants who were asked to remember them. Several were chosen to be ecologically valid, locations which a visitor to the centre would be likely to visit, for example, the post office, chemist and washrooms. Participants acting as controls received no simulation training, but were also taken to the shopping centre and carried out the tasks.

Figure 2. *The simulation of the shopping centre, which was explored before visiting the real place.*

Two days after the final exploration session, all participants were taken to the real shopping centre. Participants were tested individually. They were taken to real locations that corresponded to the viewpoint positions in the VE. Using the hand held pointing device, they were then asked to point to target objects that the VE trained participants had previously seen in the model. These objects were not visible from the testing position. Responses were recorded as vertical and horizontal angles. They were asked to complete this task from four locations within the centre. Six of the obscured targets were located on a floor above, six on a floor below and six on the same floor as the pointing location.

Additional tasks (reported in Foreman et al, submitted) required participants to walk from a starting point to a specific target location and to draw freehand sketch maps of the two floors of shops, incorporating as much landmark information as possible.

4.4 Results and Discussion

Compared with control groups who made guesses, both undergraduate and senior citizen experimental groups were more accurate in making pointing judgements toward non-visible targets, F (3,28) = 12.61; p <.001, post hoc Tukey tests revealed that both experimental groups were significantly more accurate than their corresponding controls (students: p <.006, senior citizens: p <.001). The student and senior citizen experimental groups were not significantly different from one another (p > .5).

Analysis of the judgements of level (below versus same for upper, and above versus same for lower, floor pointing locations) showed that experimental groups indicated the correct level (students: 75.7%, senior citizens: 60.4%) more often than controls, who scored at chance (students: 50.0%, senior citizens: 50.7%). When the two experimental groups were compared with the combined controls, groups differed significantly, F (2,29) = 24.5; p < .001. Student and senior citizen experimental groups both scored higher than controls (both p's < .001) but the two experimental groups also differed, students scoring higher (p < .01). Two out of eight senior citizens in the experimental group performed at chance level throughout.

Despite the widely accepted notion of deterioration of spatial functions with age, this study shows that many elderly people remain spatially competent and that age is not a barrier to the beneficial use of simulated environments for training. Wider use and adaptation of this technology might improve social inclusion in older populations by encouraging their confident use of public buildings. The present results suggest that a VE can be used beneficially not only by younger participants, but also by the elderly to enhance their spatial knowledge of an unfamiliar public building.

4. CONCLUSIONS

We have discussed two studies using simple multi level VEs. The data from these studies provides novel evidence for a vertical asymmetry in spatial memory, where downward spatial judgments are more accurate than upward spatial judgements in adults, able-bodied children, and children with physical disabilities. It will be interesting to examine this effect in a real-world environment. The results of these studies have important implications for multi-level VEs for training. A third study examined the use of a simulation of a multi-level complex shopping centre for training. Elderly people's spatial knowledge in the real-world shopping centre was examined following exploration of the simulation. This study indicates the potential of VEs as a training medium for the elderly. More work needs to be carried out to examine vertical spatial judgments in this type of complex environment.

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