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Movement Around Real and Virtual Cluttered Environments

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Abstract

Two experiments investigated participants' ability to search for targets in a cluttered small-scale space. The first experiment was conducted in the real world with two field of view conditions (full vs. restricted), and participants found the task trivial to perform in both. The second experiment used the same search task but was conducted in a desktop virtual environment (VE), and investigated two movement interfaces and two visual scene conditions. Participants restricted to forward only movement performed the search task quicker and more efficiently (visiting fewer targets) than those who used an interface that allowed more flexible movement (forward, backward, left, right, and diagonal). Also, participants using a high fidelity visual scene performed the task significantly quicker and more efficiently than those who used a low fidelity scene. The performance differences between all the conditions decreased with practice, but the performance of the best VE group approached that of the real-world participants. These results indicate the importance of using high fidelity scenes in VEs, and suggest that the use of a simple control system is sufficient for maintaining ones spatial orientation during searching.

1 Introduction

Potentially, one of the most valuable types of application for virtual environments (VEs) is training spatial behavior for real world spaces (Durlach et al., 2000). Adding credibility to the use of VEs for this purpose is the fact that research shows that the structure of spatial knowledge acquired from a VE is broadly similar to that gained from the real world (Ruddle, Payne & Jones, 1997). In fact, navigation is fundamental to many different types of VE application, whether or not there is an equivalent real world setting. The ability to navigate and orientate oneself within a VE has a direct impact on a user's ability to perform spatial tasks and will, therefore, influence the overall success of using an application, be that for training, understanding the relationship between different attributes of data, or some other purpose.

Despite the similarities between virtual and real world spatial behavior, research has shown that participants learn spatial knowledge significantly more slowly in VEs than in the real world (Richardson, Montello & Hegarty, 1999; Witmer, Bailey, Knerr, & Parsons, 1996). The difficulty that people have completing spatial tasks in VEs has been shown to exist not only in large scale VEs such as virtual buildings and seascapes, (Darken, Sibert, 1996; Ruddle, Payne, & Jones, 1998) but also in small-scale VEs, like rooms that contain obstacles to movement (Ruddle & Jones, 2001). The root cause of the difficulties people experience is often assumed to lie in the reduction of sensory information presented in the VE when compared with the real world, and the relative crudeness of the interfaces that are used for movement in VEs (Jacobson & Lewis, 1997; Waller, Hunt, & Knapp, 1998).

This article describes two experiments that investigated participants' navigational behavior when they searched two similar cluttered environments. The experiments tackle the root causes mentioned above from two complementary directions by: (i) degrading real world sensory information (substantially reducing the field of view (FOV) to 20 x 16 degrees; Experiment 1), and (ii) increasing VE fidelity in terms of the visual scene and mechanism used for movement (Experiment 2). Taken together, the experiments extend previous research into the navigation of small-scale (room-sized) VEs (Ruddle, & Jones, 2001).

2 Background

In the study by Ruddle and Jones (2001) participants were asked to travel around a small-scale VE searching for eight targets in amongst sixteen possible locations (for a definition of small-scale, see Weatherford, 1985). Given that the task was assumed to be trivial to conduct in the real world, it was surprising that participants only completed many of the trials after revisiting large areas of the environment, often several times. It seemed that participants became disorientated and unable to remember where they had previously searched. These results occurred despite being able to see the entire environment from any location simply by turning around, and that by searching the space with a systematic strategy one could ensure each possible target was visited only once.

To explain the difficulties that participants encountered, three categories of errors where identified. One was where a participant traveled adjacent to a target; but did not look in its direction; this was termed as a miss. The other categories were where the participant did not search the immediate locality or general region of the target, and these errors were called local or global neglect, respectively.

It was hypothesized that there were three primary causes for these errors. The first was participants' limited FOV and, while increasing it from 48 degrees to 103 degrees eliminated all of the misses, a notable number of inefficient searches remained by local and global neglect (Ruddle & Jones, 2001). The two other primary causes related to the mechanism participants used to move around the VEs, and the fidelity of the visual information that was presented. These are part of interface and environment fidelity, respectively (Waller et al., 1998). Further background to all three factors is described in the following sections.

2.1 Field of View

The effects of FOV have been studied for both real world and VE spatial tasks. In one well known real-world study (Alfano & Michel, 1990) participants were asked to reconstruct the layout of a space viewed with a FOV that ranged from normal to 9 degrees. The restricted FOV not only distorted participants' perception of the size of the space, but also reduced their ability to accurately reconstruct the spatial layout using color-copied photographs. However it was only with a very narrow FOV (22 degrees or less) that participants' performance was significantly worse than with a normal FOV. A more recent study investigated egocentric distance perception in the real world using a visually directed walking task (Creem-Regehr, Willemsen, Gooch, & Thompson, 2003). Participants were first shown a target and then had to walk to its position while blindfolded. Participants who used a restricted FOV (42 x 32 degrees) were just as accurate as those who viewed the target with a normal FOV. However, simultaneously eliminating head rotations by using a neck brace and restricting the FOV produced systematic underestimation of the distance to the target, but the reason for this remains an open question.

Studies that require participants to estimate distances and perform other spatial tasks in VEs often suggest that the restricted FOV contributes toward poor spatial performance. For example, when participants judged egocentric distance while wearing a HMD, they underestimated the distances while using a wide FOV (140 x 90 degrees) but overestimated the distances while using a narrower FOV (60 x 38.5 degrees; Kline & Witmer, 1996). More recently, Czerwinski, Tan and Robertson (2002) showed that with a novel navigation technique (the faster participants moved forward the higher and steeper they viewed the VE) males performed better than females with a narrow FOV, but when the FOV was widened females performance increased to equal that of males. In studies that used a task similar to the present study, participants who used a wide FOV (103 or 144 degrees) performed faster than those who used a 48-degree FOV, although the difference was not significant when the wide FOV was displayed across three monitors rather than distorted onto one (Lessels & Ruddle, 2004; Ruddle & Jones, 2001).

There are also VE studies that have shown no influence of FOV for spatial tasks. In one, participants performed a series of triangle completion tasks using a large projection screen, and accuracy was influenced by path layout but not by FOV (Péruch, May, & Wartenberg, 1997). Another investigated participants' ability to estimate ego-rotations (Schulte-Pelkum, Riecke, von der Heyde & Bülthoff, 2002). There was no difference between two FOVs presented on a projection screen (86 x 64 degrees, and 40 x 30 degrees), but with both of these participants were significantly more accurate than when the judgments were performed using a 40 x 30 degree HMD. In summary, the effect of a narrow FOV on complex spatial tasks remains an open research question.

2.2 Movement

Our ability to move around a virtual space directly influences our perceptions of that space. The design of the movement interface, and a users' proficiency at using it will, therefore, directly influence their ability to perform spatial tasks. In fact, proficiency with the interface, measured by timing participants' performance on various simple navigational tasks in a VE maze, has been shown to be one of the most important factors affecting individuals' ability to perform spatial tasks in large-scale VEs (Waller, 2000).

There are three main directional elements to movement in a VE: the direction of a person's view, the orientation of their body and their direction of travel. Altering the relationship between these three elements creates the three primary walking metaphors used for travel within virtual environments (Ruddle & Jones, 2001). The first of these is view-direction (gaze-directed) travel (Bowman, Johnson & Hodges 2001; Bowman, Koller, & Hodges, 1997) where the heading of the body, the direction of travel, and the direction of view are all locked together; the user can only travel in the direction they are looking. The second is body-direction travel where the heading of the body and the direction of travel are locked together, but one can manipulate the direction of view independently of the other two. Lastly there is independent movement where one can travel independently of both the viewing direction and body direction. Independent movement is the method that most closely resembles natural human movement. As one progresses from view-direction, to body-direction, and then independent movement, there are an increasing number of degrees of freedom (DOFs) available to the user.

A characteristic of VE navigation is that people tend to travel in paths that are generally straight (Ruddle & Jones, 2001). This is perhaps caused by the design of the movement interface, and if a greater number of DOFs are available to a user (e.g., by implementing independent rather than view-direction travel) then it will be easier for them to deviate from a straight-line path, lowering the likelihood of errors such as local and global neglect. Of course, people are more likely to exploit these additional DOFs if they are controlled in a coordinated and, ideally, natural manner.

Finally, it is hypothesized that the greater the number of DOFs available to the user the greater the cognitive effort required to control the interface, so a high DOF interface generally takes more time to learn than one with fewer DOFs. Thus, interfaces that provide a large number of DOFs (flexible movement) have both advantages and disadvantages.

2.3 Visual Characteristics

Waller, et al. (1998) introduced the concept of environmental fidelity, that is, how closely a VE resembles its corresponding real world scene. Environmental fidelity has many different factors, including the structure of an environment, its visual characteristics (e.g., whether every real-world object is included in a virtual scene, and the detail with which each object is modeled), and other sensory information. The present study is only concerned with one component of environmental fidelity: the visual characteristics.

Visual characteristics are one of the primary sources of information that people use to determine their position and orientation within an environment. The role of visual information is particularly important in VEs, where there is often no non-visual sensory information and the movement interface uses abstract controls (e.g., mouse and keyboard). There is no common metric that can be applied to measure the overall content of a scene for the availability of navigational cues, but two attributes of the visual scene that are particularly important are texture and landmarks.

Textures have been shown to affect spatial tasks in three different ways. First, the textures enhance optic flow, which has been shown to aid navigation and facilitate path integration (Kirschen, Kahana, Sekuler, & Burack, 2000; Kearns, Warren, Duchon, & Tarr, 2002).

Second, repetition (tiling) of textures such as a brick pattern conveys metric information that significantly improves participants' accuracy when estimating distances (Sinai, Krebs, Darken, Rowland, & McCarley, 1999). However other types of textures such as grass, carpet and abstract patterns had no effect on the accuracy of participants' distance estimations (Sinai et al. 1999; Witmer & Kline, 1998). This suggests that certain types of textural information could be valuable for maintaining one's spatial orientation in VEs, particularly in the absence of useful landmarks and proprioceptive information.

Third, texture mapping has been used for many years as a cost effective method for improving the visual realism of scenes, for example for building facades, trees, and signs. These types of textures often either are, or contain, distinctive "objects" that act as landmarks and could also be modeled as 3D geometry. The availability and type of landmarks are well known to influence participants search performance in VEs. For example, Steck and Mallot (1997) showed that participants stored both local and global landmarks in memory during a VE familiarization phase, and relied on one for navigation when the other was removed. The saliency of landmark cues has also been shown to influence navigational performance. In this respect, participants' route-finding accuracy has been shown to increase when everyday (i.e., familiar) objects were used as local landmarks, but not when colored patterns were used instead (Ruddle et al., 1997). Tlauka and Wilson (1994) found that landmarks were useful for wayfinding when other strategies, specifically counting left and right turns, were suppressed by an artificial increase in workload (backward counting).

Finally, the majority of studies that have investigated VE navigation have deliberately used bare and simplistic virtual scenes, albeit often texture mapped.

However, a notable exception was a study that compared the acquisition of route knowledge from a high fidelity VE building with other training media (Witmer, Bailey et al. 1996). This found that participants who were trained in a VE made more navigational errors than those trained in the real world, but fewer errors than participants who trained by being shown pictures. In summary, as would be expected, visual detail is beneficial for spatial tasks.

3 Overview of the Experiments

The experimental task was essentially the same as the task for the original VE study (Ruddle & Jones, 2001). Participants were asked to travel around a small 10m x 10m cluttered environment searching for eight targets in amongst 16 possible locations. To do this search task efficiently participants had to remember where they had traveled and minimize the extent to which they retraced their steps.

In Experiment 1 participants performed the task in the real world. The experiment was conducted to investigate two factors. First to confirm what had been assumed in the previous VE study, that this task would be trivial to perform in the real world, and to provide a “gold standard” of participants’ performance for future research. Second, to investigate participants’ performance when their FOV of the real world scene was substantially restricted (to 20 x 16 degrees in each eye). Considering that a restricted FOV has been shown to hinder participants’ ability to perform simple real world spatial tasks, it was hypothesized that restricting the FOV for this real world search task would produce a decrease in performance (slower search or greater distance traveled) when compared to participants with no visual restrictions.

Experiment 2 then investigated four combinations of visual scene characteristics (low- vs. high-fidelity) and movement interface (forward-only vs. 4-way movement) when the task was performed in a VE. The low fidelity scene was similar to the scene used by Ruddle and Jones (2001), whereas the other scene was a high-fidelity model of the real world environment used in Experiment 1. The forward-only movement interface was similar to the interface used in Experiment 3 of Ruddle and Jones (2001). Two hypotheses were made: (i) the high-fidelity VE would produce an increase in task performance over a low-fidelity scene, and (ii) participants performance would also be increased with the independent interface than with the simple (forward-only) interface that was used in the earlier study. Taken together, the experiments investigated the difficulties participants have searching small-scale spaces by degrading real world fidelity and increasing the fidelity of a VE. Both experiments followed the general procedures of VE experiments laid down by the School of Computing, and all participants gave their informed consent.

4 Experiment 1

The real world experiment was conducted over two days in the university's sports hall. A between participants design was used, with participants randomly allocated to either the full-view (normal) or restricted-FOV condition.

4.1 Method

4.1.1. Participants. Ten participants took part in the experiment. Their ages ranged from 18 to 36. All participants were either graduates or undergraduates who volunteered for the experiment and were paid an honorarium for their participation.

4.1.2. Materials. The design of the real environment (see Figure 1) was comparable to the original VE study. The environment contained 33 corrugated paper cylinders, all measuring 0.5m in diameter and 1.35m high. A climber's rope was placed around the perimeter of the cluttered environment, substituting the colored walls that defined the space in the original VE. The configuration of the cylinders was the same as in the original VE, 32 cylinders arranged in eight identical groups of four, with the 33rd cylinder positioned in the center (see Figure 2). On top of 16 of the cylinders was placed a small box, which indicated a possible target location. Eight of the boxes contained a target and the remaining eight were empty (decoy boxes).

Figure 1 here

Figure 2 here

The design of the cylinders was modified from the original study to help the authors analyze participants' behavior as they conducted the search task. In the original study the presence of a blue-topped cylinder signaled a possible target location (see Figure 3), and targets were placed in a recess in the blue top so they were visible whenever participants were within a distance of 0.747 meters and looking in the appropriate direction. However, during data analysis it was not possible to distinguish between occasions when participants traveled to a blue-topped cylinder to check for a target inside, and occasions when participants passed one of the cylinders while en-route to another. To prevent this ambiguity in the real world study, the targets and decoys were indicated by the presence, on top of a cylinder, of a small white plastic box with a blue lid. The target boxes each contained a target object (a small square piece of red card) while the decoy boxes were identical but with the red card absent. With this design if a participant wanted to search a box for a target they had to lift off the lid and look inside. This indicated that the participant was making a conscious decision to search for a target in that box.

In the restricted-FOV condition, participants wore modified safety goggles (see Figure 4) that reduced each eye's FOV down to approximately 20 degrees on the horizontal and 16 degrees in the vertical direction.

Figure 3 here

Figure 4 here

4.1.3. Procedure. The procedure for the real world experiment was similar to the procedure used in the original VE study. Each participant performed four trials. The first was treated as a practice trial and the three subsequent trials were treated as test trials. Participants performed the trials individually and took approximately 35 minutes to complete the experiment.

For each trial, a participant was given eight pieces of blue card and asked to walk around the environment depositing these cards on top of the eight red cards (target objects) inside the target boxes. This ensured that if they revisited a target box during a trial, they would know this by the presence of the previously deposited blue card. Participants were asked to walk at a normal speed, minimize their journey path, avoid checking each possible target location more than once, and asked to place each box lid back the way they had found it so that they wouldn’t be able to know, simply by looking at the lid, if they had already visited that box during that trial. To prevent participants seeing the positions of the boxes before the beginning of the trial, they waited outside the sports hall while the targets and decoys were placed in position, and then blindfolded while being guided to the starting point for each trial (the boundary recess; see Figure 2). The start of the trial was signaled by the removal of the blindfold.

Participants searched until they had found all eight targets, and then left the hall and waited outside while the boxes were repositioned ready for the next trial. No feedback was provided on participants’ performance or the search strategy that had been adopted. The procedure for the participants under the restricted-FOV condition was the same except they conducted the trials whilst wearing the view restricting goggles. These participants were asked to look at the floor while they were guided to the starting point, and the restricted view rendered the blindfold unnecessary.

The positions of the target and decoy boxes, for each trial, were defined by the same rule used to position the blue-topped cylinders in the original study. That is, within each group of four cylinders one was randomly chosen to be the target and another a decoy. This ensured that the targets and decoys were distributed around the environment.

During each trial three types of data were recorded. First, the time that each participant took to complete the task was recorded. Second, the route that each participant traveled was sketched on a plan of the environment. Finally, each trial was recorded on videotape, which was then used after the experiment to confirm both the time taken and the route traveled.

4.2 Results

Participants' performance in each trial was measured using two primary types of data:

1. Task performance
    a. Time taken to find the eight targets
    b. Total number of visits to target and decoy boxes during a trial
    c. Distance traveled (percentage above the optimum route length)
2. Behavior
    a. Search strategy

Statistical analyses of the data were performed using mixed design analyses of variance (ANOVAs) that treated the field of view as a between participants factor (full-FOV vs. restricted-FOV) and the trial number as a repeated measure. Only data for the three test trials were analyzed. None of the interactions were significant.

4.2.1. Task performance. Due to an error, time data for the first test trial of one participant were not recorded. The time that participants took in the full-FOV (M = 94.4 s, SD = 26.9) and restricted-FOV conditions (M = 104.3 s, SD = 22.0) was similar ($F(1, 7) = 0.95$, $p > .05$). Also, the time taken in the test trials did not change significantly as the test trials progressed ($F(2, 14) = 0.47$, $p > .05$). Participants started to search the environment as soon as the trail started, stopped momentarily to check the boxes, although sometimes participants simply slowed down, and rarely stopped between target or decoy boxes to look around.

The total number of visits to target and decoy boxes for the two FOV conditions did not differ between FOV conditions (M = 15.3 in both cases), or between the three test trials. In 26 of the 30 trials participants did not revisit any target or decoy boxes, meaning that these trials were completed with optimal efficiency according to this metric. In the full-FOV condition, one participant revisited two boxes in one trial and, in the restricted-FOV condition, three separate participants each revisited one box in one trial.

The distance that participants traveled was compared to the shortest possible distance, calculated using a traveling salesperson problem (TSP) algorithm. First the distance traveled by a participant in a trial was approximated by calculating the straight line distance between the start point and the centers of the target and decoy boxes, in the order that they were visited.

The TSP program used to calculate the shortest possible route was written in C++ by the authors and utilized an algorithm obtained from the Combinatorial Object Server (Ruskey & Sawada, 2002). Unlike conventional TSP algorithms, the software implemented did not have to find a solution that started and finished in the same place. Instead it found the shortest route for a one-way, outward-bound trip, which ended at the last visited target.

An example of an actual route taken by a participant in a trial and the corresponding solution calculated by the TSP program is shown in Figure 5. In this example the participant did not visit the last decoy box because the task was complete when the eighth, and final, target was found. The program, however, included this decoy (circled) as part of its initial solution but then remedied the inconsistency by subtracting the last route segment from the distance that was calculated. The TSP program then drew the shortest route on a plan view using OpenGL.

Figure 5 here

In each trial, the distance that participants traveled was derived by expressing the distance that participants traveled as a percentage above (or below) the distance of the shortest possible route. There was no significant difference in this percentage between full-FOV (M = +10.5%, SD = 13.5) and restricted-FOV conditions (M = +15.0%, SD = 18.4), ($F(1, 8) = 0.37$, $p > .05$), or between the three test trails ($F(2, 16) = 0.03$, $p > .05$). The only trial in which there was an exact match between the path taken by a participant and that calculated by the TSP program is the one shown in Figure 5.

Some participants walked a path shorter than the TSP program solution because, while searching for the eight targets, they passed some decoy boxes and fortuitously left them un-searched. A similar behavior was also observed in the original VE study where participants traveled past a decoy but did not search it.

Considering these performance measures, as predicted, participants completed the task with near perfect efficiency. Even with a restricted field of view, the task was trivial to perform.

4.2.2 Behavior. Inspection of the paths followed in the two experiments described in this article showed that participants usually started their search by either following the perimeter of the VE or adopting a lawnmower-type pattern. In most trials, participants found the majority of the targets using one of these two strategies. Any remaining targets were then searched for using secondary strategies, examples of which included spiraling in on the center of the VE after completing a search of the perimeter, and the somewhat random searches that occurred when participants were unsure of which targets and decoys they had already visited.

Interest in the present study is centered on participants' initial (primary) search strategies. For each trial, these were analyzed using a three-stage process:

1) Classifying the strategy as *perimeter*, *lawnmower*, or *other*.
2) Counting the number of passes made during the search.
3) Counting the number of targets found before any revisitation.

Searches were classified by dividing the VE into four quadrants and noting the order in which these were visited. Perimeter searches visited the quadrants in the order 1-2-3-4-1 (clockwise search; see Figure 6a) or 1-4-3-2-1 (anticlockwise). Lawnmower searches involved a sequence of passes that crossed the VE's centerline, progressing along the centerline from one side of the VE to the other. The centerline was always perpendicular to the direction of the passes, so in some trials this was the dividing line between quadrants 1/2, and 3/4 (see Figure 6b), but in other trials it divided quadrants 1/4 from quadrants 2/3. All lawnmower searches were predominately in line with the circulation routes created by the structure of the cylinders; no lawnmower search was conducted that progressed diagonally across the environment. One search in each FOV condition could not be unambiguously classified as perimeter or lawnmower, and so were termed as ‘other’.

Figure 6 here

The second stage of the process was to count the number of times the centerline was crossed (the number of ‘passes’) during the primary phase. A perimeter search always had two passes, and a lawnmower search usually had three or more. The final stage involved counting the number of targets that were found by each search up until any target or decoy was revisited.

The results for the three stages of the search strategy analysis are summarized in Table 1. In the full-FOV condition, participants used a perimeter strategy for most of their searches, but a lawnmower strategy was dominant in the restricted-FOV condition. In all but one of the perimeter and lawnmower searches participants found all of the targets during the primary phase of the search. In the lawnmower searches participants made an average of four passes of the environment (up, down, up and then down again) compared with two for the perimeter searches. When using a lawnmower strategy participants tended to focus on a narrow “strip” of the environment during each pass, but with the perimeter strategy participants deviated from the edge of the environment to visit the targets and decoys that were nearby. The distance that participants traveled in excess of the shortest route was lower for trials performed using a perimeter strategy (M = 7.5%, SD = 15.8) than a lawnmower strategy (M = 19.2%, SD = 16.0).

Table 1. *Number of searches carried out with each strategy in experiment 1, and mean number of targets found and passes made with those strategies.*

Group	**No. searches**			**Mean no. of targets found before repetition**			**Mean no. of passes**		
	Perim.	**Lawn.**	**Other**	**Perim.**	**Lawn.**	**Other**	**Perim.**	**Lawn.**	**Other**
full-FOV	11	3	1	7.91	8.00	8.00	2.0	3.7	2.0
restricted-FOV	4	10	1	8.00	7.30	5.00	2.0	4.2	2.0
Both groups	15	13	2	7.93	7.46	6.50	2.0	4.1	2.0

4.3 Discussion

Restriction of the participants' FOV had no effect on participants' search performance in this real-world cluttered space, but did affect the strategy they adopted. Two clear types of strategy were chosen by the participants (perimeter and lawnmower), with the perimeter strategy being dominant in the full-FOV condition, and the lawnmower strategy dominant in the restricted-FOV condition. One explanation could be that by reducing their FOV to such an extreme, (20 x 16 degrees.) these participants were forced to consider only nearby cylinders and were unable to plan an efficient route through the environment by considering the space as a whole. The resulting lawnmower strategy increased the number of changes in direction made by the participants throughout the trial, compared to the perimeter search, but because the real world offers such a rich source of proprioceptive and visual orientation cues, the restricted-FOV group did not become disorientated, and so did not visit significantly more targets and decoys than the full-FOV group. Overall and with both strategies, participants found the experimental task trivial to conduct, completing it with near perfect efficiency.

Two note-worthy comparisons may be made with the results of Ruddle and Jones (2001), who compared the performance of participants who used either a 48 or 103 degree FOV in a desktop VE to perform a task similar to the one used in the present real-world experiment. First, restricting a participant's real-world FOV had negligible effect on the time it took to complete the task, but in a desktop VE this restriction increased the time by approximately 40%. Second, restricting the real-world FOV had little effect on the number of targets and decoys visited, but in a VE caused a three-fold increase in the percentage of trials where participants had great difficulty completing the task and had to revisit at least half of the environment.

5 Experiment 2

As hypothesized, participants found the search task trivial to perform in a real world cluttered environment whereas the same task has been found to be very difficult to perform in a VE. Experiment 2 was conducted to bridge the gap between the original VE study and the real world environment used in Experiment 1 by investigating the effect of different movement interfaces and visual scene characteristics on participants' search performance in a VE.

Experiment 2 used a 2 by 2 between participants design. Participants were randomly allocated to one of four conditions that each used one of two movement interfaces and one of two visual scenes. With one movement interface participants could only travel forwards (the *forward-only* condition), but the other allowed the participants to travel any combination of forwards, backwards, left and right (the *4-way* movement condition).

One visual scene condition used a VE with a high resolution model of the sports hall (the *high-fidelity* scene condition). The other used the cylinder environment without a background (the *low-fidelity* scene condition) and was equivalent to the environments used in the original VE study. The high-fidelity scene condition replicated the real world sports hall and used textures captured by digital camera from the floor, walls, and ceiling of the sports hall used in the real world environment of Experiment 1 (see Figure 7). All four experimental conditions were implemented using desktop VEs.

Figure 7 here

Method

5.1.1 Participants. Twenty-two participants (11 females and 11 males) took part in the experiment, and their ages ranged from 18 to 40. After a period of 50 minutes one participant failed to complete a single practice trial, even with extended tuition, and so did not progress through to the test trials. Another participant withdrew due to symptoms of VE sickness. Both of these participants were replaced in the experiment. Presented here are the results of the 20 participants who successfully completed the experiment, including a third participant who suffered from nausea in the last test trail but still finished the experiment. All participants were either graduates or undergraduates who volunteered for the experiment and were paid an honorarium for their participation.

5.1.2 Materials. Experiment 2 used a modified version of the software used in the original Ruddle and Jones (2001) study, adapted to reflect the changes made to the decoy and target boxes in the real world environment.

Participants traveled around the VE using the keyboard cursor keys for movement across the horizontal plane. Motion was continuous and at a speed of 1 m/s while the cursor keys were depressed, and stopped when released. In the forward-only condition (view-direction movement) participants could only travel forward in the direction in which they were looking, achieved by holding down the ‘up’ cursor key. In the 4-way (independent movement) condition they could move forward, back, left, and right across the horizontal plane of the VE and could also travel diagonally by holding down pairs of keys (e.g. forward and left). In both of these movement interfaces the mouse was used to control the participant’s direction of view. Looking up and down was achieved using zero order control; by moving the cursor up the screen the viewing pitch increased by up to +90 degrees, and the viewing pitch decreased by a corresponding amount if the cursor was moved down the screen. Looking left and right was accomplished using first order control with the rate of turning increasing proportionally with the cursor’s distance away from the vertical centerline of the screen. The maximum rate of turning was 135 degrees/second.

Participants could raise and lower the lids of the target and decoy boxes by pressing the left mouse button. Pressing it once raised the lid, and pressing it again lowered the lid. If there was a target present inside the box the participant pressed the right mouse button to select it, the target then turned from red to blue indicating that it had been found, comparable to the depositing of a blue card on top of a red target in the previous real world experiment. The lid was then lowered automatically by the VE software. The software prevented participants from moving away from any box until its lid was lowered. A lid could only be raised, and a target selected, if the participant was within 0.6 m of the center of the box (i.e., they were adjacent to it) and it was within the participant’s FOV.

The VE application was written in C++ and OpenGL Performer™ and ran on an SGI Onyx 3400 with a frame rate of 60 Hz, giving an overall system latency of approximately 30 ms. The VE was viewed with a 48 x 39 degree graphical FOV via a CRT color monitor with a 475 mm x 300 mm viewable screen size. The resolution was 1280 x 1024 pixels and the refresh rate was 72 Hz. All participants viewed the monocular displayed VE from a distance of approximately 60 cm.

The high-fidelity scene condition used images of the sports hall surfaces as textures, these were captured using a digital camera and ‘stitched’ together to create seven separate textures: each of the 4 wall textures were 1024 x 512 pixels (1.5 Mb each in RGB format); the floor texture was 2048 x 1024 pixels (6.1 Mb), and the ceiling texture was 512 x 128 pixels (0.4 Mb). The seventh texture was used to replicate the appearance of the 25 lights, suspended from the sports hall ceiling (0.1 Mb each).

5.1.3 Procedure. Participants were randomly allocated to one of the four conditions, were run individually, and took approximately 45 minutes to complete the experiment. Each participant first practiced using the interface until they could fluently use the controls. The participant then performed two practice trials that allowed him or her to become familiar with the search task, and then completed four test trials.

As in experiment 1, all participants were asked to minimize their journey path and to avoid checking each possible target location more than once. Each trial began at the starting point in the boundary recess (see Figure 2) and participants searched until they had found and selected all eight targets, as in experiment 1. Participants were informed that the targets were always in the white boxes, but that their positions changed between trials. No feedback was provided on participants’ performance or their search strategy.

5.1 Results

Participants' performance in each trial was measured using the same task performance metrics as Experiment 1, but additional behavioral metrics were used:

1. Task performance
    a. Time taken to find the eight targets
    b. Total number of visits to target and decoy boxes
    c. Distance traveled
2. Behavior
    a. Movement key usage
    b. Search strategy
    c. Errors

Statistical analyses of the data followed the same method as Experiment 1 and were performed using mixed design ANOVAs that treated the scene (high- vs. low-fidelity) and movement interface (forward-only vs. 4-way) as between participants factors, and the trial number as a repeated measure. None of the interactions were significant.

5.2.1 Task performance. Participants performed the searches significantly quicker with forward-only movement than with 4-way movement ($F(1,16) = 5.93$, $p < .05$), and significantly quicker in the high-fidelity scene than the low-fidelity scene ($F(1,16) = 8.16$, $p < .05$). Participants also performed the searches significantly quicker as the trials progressed ($F(3,48) = 2.93$, $p < .05$), with most of the difference between the conditions occurring in Trials 1 and 2 (see Figure 8).

Figure 8 here

In terms of statistical differences, the pattern of results for the number of visits to target and decoy boxes, and the percentage distance traveled above the minimum were identical to the time data. Participants visited fewer targets and decoys with the forward-only interface than the 4-way interface (*M* (*SD*) = 18.0 (6.4) vs. 22.6 (12.2); $F(1,16) = 6.17$, $p < .05$), fewer with the high-fidelity scene than the low-fidelity scene (*M* (*SD*) = 17.8 (6.6) vs. 22.8 (12.0); $F(1,16) = 7.45$, $p < .05$) and fewer as the trials progressed ($F(3,48) = 3.10$, $p < .05$). Participants traveled shorter distances with the forward-only interface than the 4-way interface (*M* (*SD*) = 44.2% (71.7) vs. 84.1% (104.0); $F(1,16) = 4.55$, $p < .05$), shorter distances with the high-fidelity scene than the low-fidelity scene (*M* (*SD*) = 41.5% (60.0) vs. 86.8% (110.1); $F(1,16) = 5.87$, $p < .05$) and shorter distances as the trials progressed ($F(3,48) = 2.80$, $p = .05$).

5.2.2 Behavior. Three behavioral measures were used. First, the VE software automatically recorded the amount of time participants held down each of the keys that were used to control movement. Overall, participants held down a movement key for 12.8% of the trial time (excluding time when a box lid was raised and participants were prevented from changing position), and in this there was little difference between the four combinations of scene and movement interface, or the four trials. However, there was a marked difference between use of the 4-way movement interface with the two visual scenes. With the high-fidelity scene, participants used the forward key for 99.7% of the time they spent moving, and the left and right keys for the remaining 0.3%. In fact, three of the five participants in this group never used the left or right key. With the low-fidelity scene, participants used the forward key for 71.1% of the time, the backward key for 12.0%, and the left and right keys for 16.9%.

Second, participants' primary search strategies were classified using the same process as in experiment 1 (as was stated previously, the process was developed by simultaneously looking at the data for both experiments). A perimeter strategy was dominant in the 4-way movement/low-fidelity group, but lawnmower and perimeter strategies were equally prevalent in the other three groups (see Table 2). The percentage distance above the optimum distance for the participants who used the lawnmower strategy (*M* = 40.0%, *SD* = 61.2) was almost half that of the participants that chose the perimeter strategy (*M* = 78.2%, *SD* = 107.7). This is in direct contrast to the findings in the real world experiment. Although participants in all four groups took a similar amount of time to perform the task in Trials 3 and 4, inspection of the number of targets missed during the primary search shows that no forward-only/high-fidelity participant ever missed more than one target, but at least one participant in each of the other groups missed three or more targets.

Table 2. *Number of searches carried out with each strategy, mean number of targets found, and mean number of passes performed in experiment 2.*

Group	No. searches			Mean no. of targets found before repetition			Mean no. of passes		
	Perim.	**Lawn.**	**Other**	**Perim.**	**Lawn.**	**Other**	**Perim.**	**Lawn.**	**Other**
forward-only/low-fidelity	8	9	3	7.13	7.33	5.67	2.0	3.6	3.3
forward-only/high-fidelity	9	10	1	7.44	8.00	7.00	2.0	3.9	2.0
4-way/low-fidelity	15	3	2	6.60	5.67	3.50	2.0	3.3	3.0
4-way /high-fidelity	11	8	1	6.09	7.88	3.00	2.0	4.4	2.0
All groups	43	30	7	6.74	7.53	4.86	2.0	3.9	2.8

In many of the trials in experiment 2, participants traveled substantially further than they needed to, revisiting many targets and decoys. Close inspection of the data showed that participants typically quickly found the first seven targets but then had difficulty finding the eighth. This is borne out by the fact that participants traveled an average of 6.1 m to find each of the first seven targets but 18.5 m for the eighth. The cause of these difficulties was errors made by participants, which forms the basis of the third behavioral measure. For each trial, we classified the targets that were found after one or more targets or decoys had been revisited into three groups by overlaying the path a participant had followed until the first revisit onto a plan view of the environment that had been divided into sectors using Delaunay triangulation (see Figure 9). A *miss* was recorded if the participant had previously touched the cylinder on which the target's box was located. *Local neglect* was recorded if the participant had previously traveled through any of the Delaunay triangles connected to the target's cylinder. *Global neglect* was recorded for all other errors, indicating that the participant had not been in the target's immediate vicinity. Overall, global neglect was prevalent in the forward-only/low-fidelity condition, but local and global neglect occurred with roughly equal frequency in the other conditions (see Figure 10).

Figure 9 here

Figure 10 here

5.2.3. Comparison with experiment 1. A one-way ANOVA was performed to compare the mean number of visits that participants made to targets and decoys in the test trials of the two experiments. For the analysis, participants in both conditions of Experiment 1 (full-view and restricted-FOV) were combined into a single group because their performance had been almost identical. Overall there was a significant difference between the real-world and VE participants ($F(4,25) = 9.15$, $p < .01$). Planned contrasts showed that the real-world participants made significantly fewer visits than participants in the forward-only/low-fidelity, 4-way/low-fidelity, and 4-way /high-fidelity VE groups ($p < .05$), but not the forward-only/high-fidelity group. Detailed inspection of the data showed that, although the real-world and VE forward-only/high-fidelity groups visited a similar number of targets and decoys ($M = 15.3$ vs.

16.0), the latter only completed 55% of the trials perfectly (revisiting no targets or decoys) whereas the full-FOV real-world group were perfect on 93% of trials. With the exception of one of the imperfect trials, these VE participants never revisited more than two targets or decoys.

5.2 Discussion

The implementation of the movement interface had a significant effect on participants' search performance. Participants who used forward-only movement visited fewer targets, traveled a shorter distance, and took less time than participants who used the 4-way movement interface. These results echo the findings of Ruddle and Jones (2001) where the simplest movement interface was found to produce the most effective searches. However, by the third and fourth trial of the present study, participants achieved similar results with both forms of interface, but this improvement in performance was not due to a change in the type of primary search strategy that was adopted, as this rarely changed between trials.

The visual characteristics of the VE were also significant in affecting participants' ability to search the virtual space. The high-fidelity VE used large and detailed texture maps to create a visually faithful facsimile of the sports hall scene. This seems to have created a VE with adequate cues for the updating of orientation and heading across the test trials. In the condition where the most effective movement interface was used in conjunction with the most effective visual scene, forward-only/high-fidelity scene condition, participant's efficiency (number of visited boxes) was comparable to the real world.

Classification of the errors that participants made provides information about why participants searched inefficiently in many trials. Misses were rare and, as in the study by Ruddle and Jones (2001), local and global neglect occurred with similar frequency. To prevent a miss, participants simply had to turn to face a given target and select it. To prevent local neglect, participants had to move a short distance across to the target, whereas prevention of global neglect involved participants in maneuvering around the obstacles presented by other cylinders. Of particular interest is the fact that local neglect was most common with 4-way movement, despite the fact that this interface theoretically made it easiest for participants to move in any direction.

An unexpected finding was the different use of movement keys in the two 4-way conditions. Participants in the 4-way movement/high-fidelity condition used the back, left and right sideway keys for only 0.3% of the time spent traveling, while the participants in the 4-way movement/low-fidelity condition used these keys for 28.9% of the time. Both groups were shown and encouraged to use the keys in the same way, but participants in the high-fidelity condition chose to perform the task by predominantly using the forward key. It is hypothesized that the lack of a dominant frame of reference for the low-fidelity scene led participants to rely on the movement keys to navigate around obstacles, thereby maintaining their global orientation. One participant took this to an extreme and adopted a novel movement method that only used the four movement keys for navigation and did not use the mouse at all. By contrast, with the high-fidelity scene participants used the mouse to turn as they traveled forwards and used the scene content to maintain their orientation.

6 General Discussion

Two experiments were conducted using the same search task. The first experiment was performed in the real world whilst the second was performed in a VE. The experiments investigated navigation from two complementary directions, by degrading real world sensory information (reducing the FOV) and increasing VE fidelity in terms of the visual scene and mechanism used for movement.

In the real world study the majority of the full-view participants searched the environment with a perimeter strategy in a clockwise or anticlockwise direction, while the majority of the restricted-FOV participants adopted a lawnmower strategy. The restriction of participants' FOV did not increase the number of targets and decoys that were visited, compared to the full-view condition, indicating that participants were able to maintain their orientation throughout the task. What the reduction in the normal FOV took away was made up for by the increased reliance on other feedback sources (e.g., vestibular and kinesthetic), and by the use of a compensatory strategy. Even though the lawnmower strategy created a longer search path with more changes of direction, it did not produce a decrease in performance. There were no improvements in performance across trials in either condition, indicating that participants were performing at ceiling level throughout the experiment. In both conditions, using either strategy, participants performed the search task with near perfect efficiency and found the task to be trivial.

All the participants who adopted the lawnmower strategy walked a route that was predominately in line with the structure of the cylinders and the walls of the sports hall: no one walked a lawnmower path that progressed across the cylinder layout at 45 degrees to the surrounding environment. This suggests that the participants were using the frame of reference of the cylinders and/or the sports hall as a guide (Mou & McNamara, 2002).

The second experiment was conducted in a VE and contained four conditions that were used to investigate the effects of two implementations of movement interface and two fidelities of visual scene characteristic. Participants performed quickest and visited fewest targets with forward-only movement and a high-fidelity scene, and in this condition participants approached a real world level of performance. As in Experiment 1, the configurations of the traveled path fell into two main categories, perimeter and lawnmower. However, unlike Experiment 1, participants who used the perimeter strategy traveled substantially further than those who used a lawnmower strategy (a reversal of the results obtained in Experiment 1). One explanation for this is that the lawnmower strategy involves a systematic search of the environment with participants' path only influenced to a small degree by the actual positions of the target and decoy boxes. By methodically passing through the entire environment, participants found most of the targets during the primary search. By contrast, a perimeter strategy is an object location-dependant strategy that attempts to create a path joining all of the boxes together in a continuous loop. Participants using the perimeter strategy often missed a target during their primary search, making another search inevitable and increasing the distance traveled. As noted above, most participants who performed the task with a restricted FOV in the real world adopted the safer, lawnmower strategy.

Finally, this study has some important implications for the design of VEs for navigation. First, the study indicates that making an environment visually photorealistic allows navigation to take place almost as efficiently as in the real-world, although further investigations are required to bridge the gap between the low- and high-fidelity environments used in Experiment 2 and determine the minimum level of visual fidelity that is required. Questions that now might be asked are: (a) how much useable orientation and position cue information did the high-fidelity textures contain, and (b) how much of this information can be removed while still allowing people to navigate efficiently. Second, as in the study by Ruddle and Jones

(2001), participants performed best with the simplest movement interface, and this may be because the simplicity of the interface made it very straightforward to learn and allowed most of participants' cognitive effort to be allocated to the search task.

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Figure captions

Figure 1. *Photograph of the cluttered real-word scene.* [1 column]

Figure 2. *Plan view showing the layout of the 33 cylinders.* [1 column]

Figure 3. *The target and decoy cylinders used in the original study (left; Ruddle & Jones, 2001) and real world experiment of the present study (right). In the original study the cylinders had a blue top, with a target (white square) placed in a recess on the top. In the present study a plastic box placed on top identified the targets and decoys.* [2 columns]

Figure 4. *Diagrammatic view (right) and picture (left) of the modified safety goggles used for the restricted-FOV condition.* [2 columns]

Figure 5. *A sketch of a participants' route through the environment in experiment 1 (left; 'T' = target, 'D' = decoy). The shortest route, as calculated by the TSP program (right). The route ends at a decoy (circled) so the program subtracted the distance of the last route segment. In this trial, the participant followed the shortest route.* [1 column]

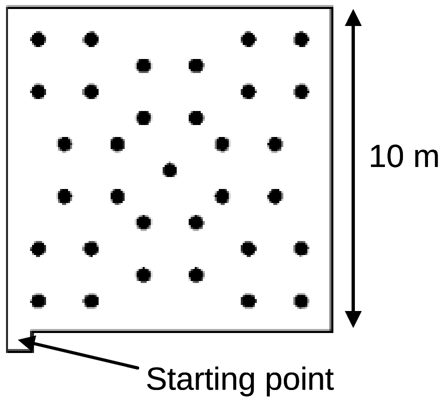
Figure 6. *Two examples of participants search paths in experiment 1, (a) perimeter search (left), and (b) lawnmower search (right). Both figures show the plan divided into quadrants, which were used for the classification of search strategies.* [2 columns]

Figure 7. *The two low-fidelity (left) and high-fidelity (right) VE scenes used in experiment 2.* [2 columns]

Figure 8. *The mean times for the four VE movement/fidelity conditions in experiment 2. Error bars indicate the standard error (SE).* [1 column]

Figure 9. *Examples of the errors made by participants. Solid line shows path up to the point that the first target/decoy was revisited, and the dashed line shows the participant's path for the remainder of the trial. Miss (left): participant's path was deflected by the target surrounded by the shaded circle. Local neglect (middle): Delaunay triangulation (shaded) defines local region around neglected target. Global neglect (right): participant did not pass through local region (shaded) until after first target/decoy was revisited.* [2 columns]

Figure 10. *Mean number of each type of error made in each trial, for each combination of fidelity and movement interface.* [1 column]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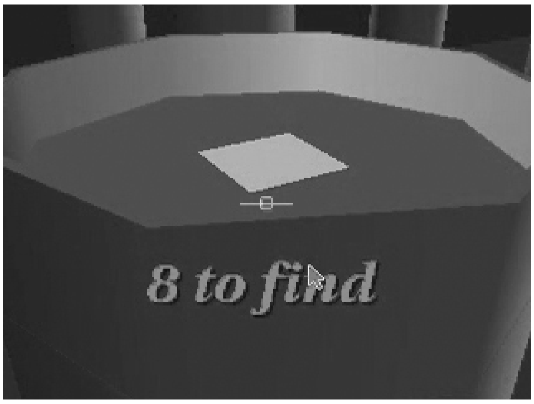
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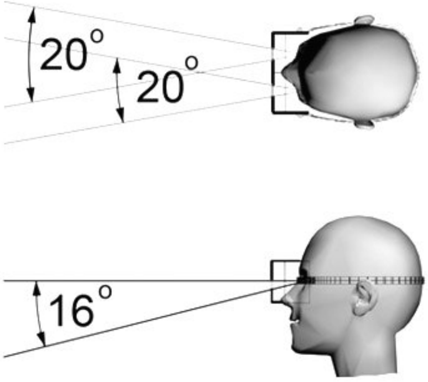

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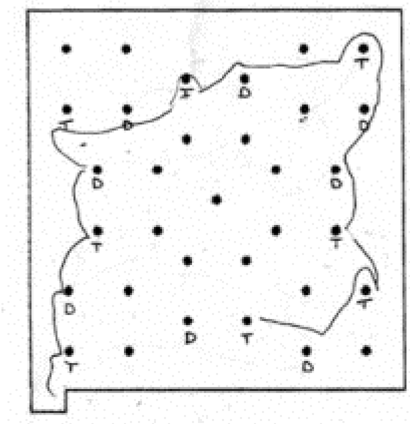

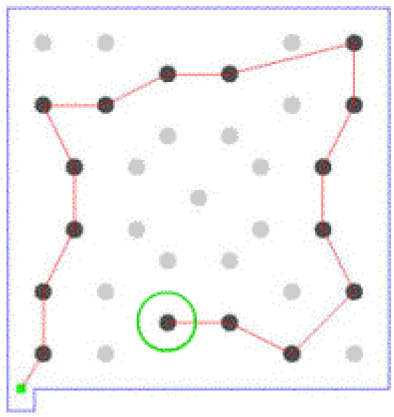

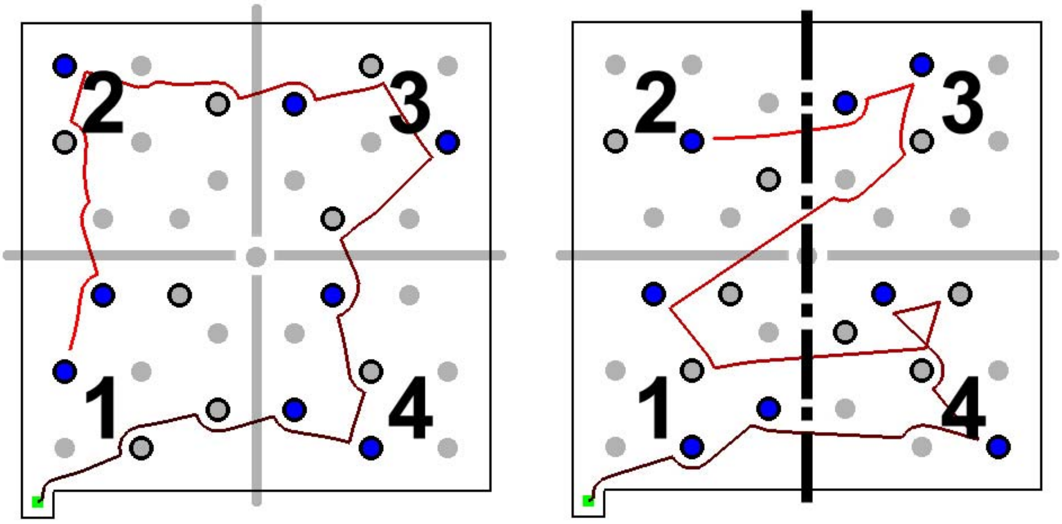
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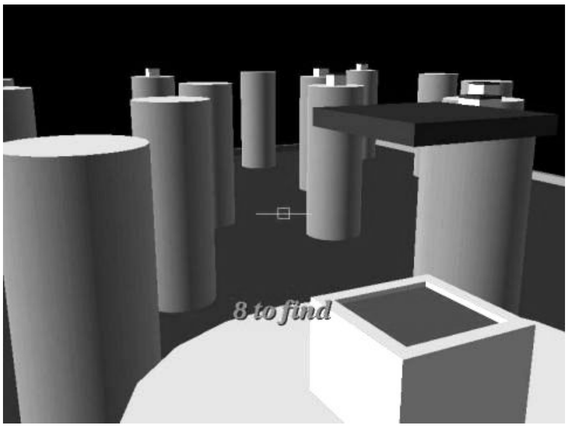
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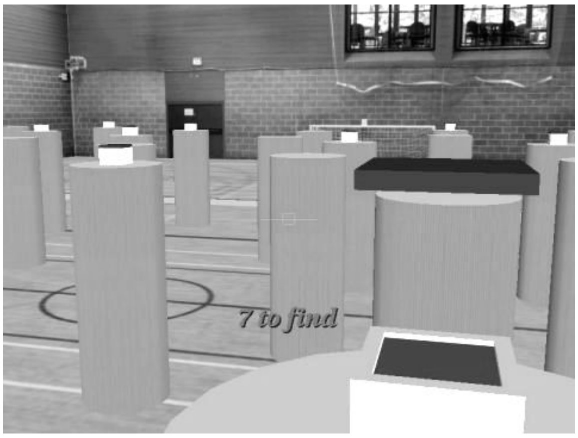
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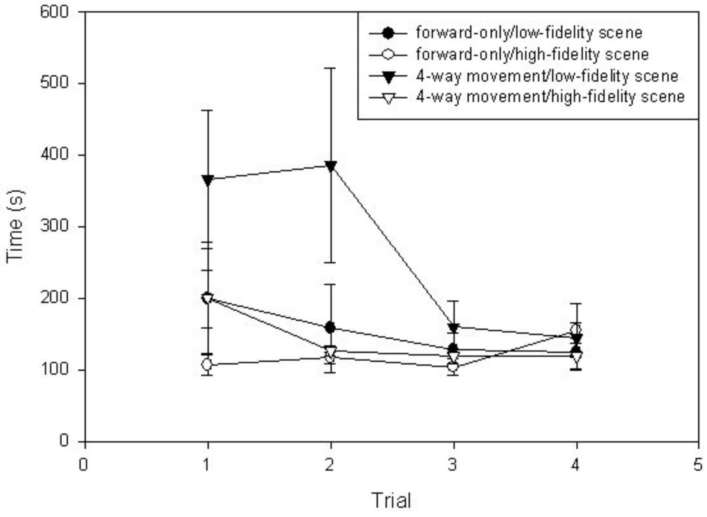

600
500
400
300
200
100
0
Time (s)
0
1
2
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4
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Trial
forward-only/low-fidelity scene
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4-way movement/low-fidelity scene
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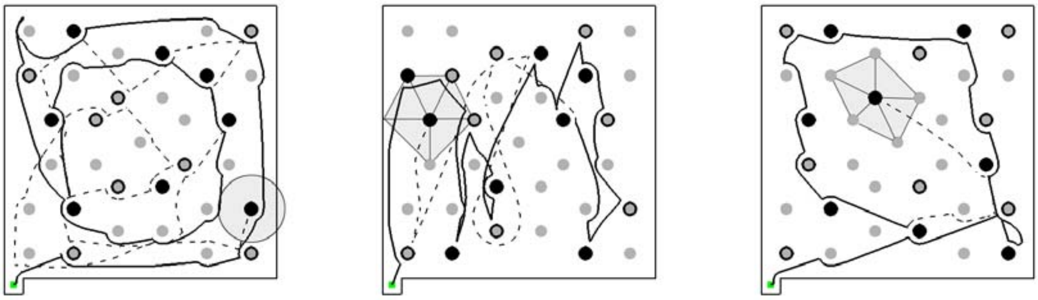

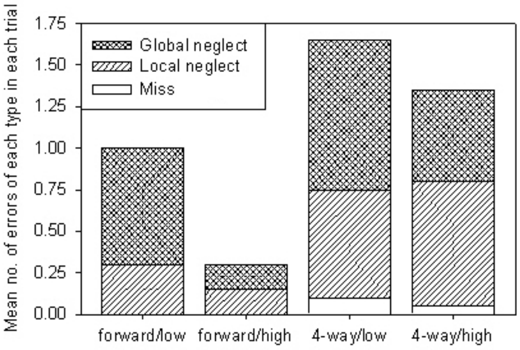

Mean no. of errors of each type in each trial
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Global neglect
Local neglect
Miss
forward/low
forward/high
4-way/low
4-way/high