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Published paper
Ruddle, R.A. and Lessels, S. (2009) *The benefits of using a walking interface to navigate virtual environments.* ACM Transactions on Computer-Human Interaction, 16 (1). 5:1-5:18.
http://doi.acm.org/10.1145/1502800.1502805

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The Benefits of Using a Walking Interface to Navigate Virtual Environments

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Navigation is the most common interactive task performed in three-dimensional virtual environments (VEs), but it is also a task that users often find difficult. We investigated how body-based information about the translational and rotational components of movement helped participants to perform a navigational search task (finding targets hidden inside boxes in a room-sized space). When participants physically walked around the VE while viewing it on a head-mounted display (HMD) then they performed 90% of trials perfectly, comparable to participants who had performed an equivalent task in the real world during a previous study. By contrast, participants performed less than 50% of trials perfectly if they used a tethered HMD (move by physically turning but pressing a button to translate) or a desktop display (no body-based information). This is the most complex navigational task in which a real-world level of performance has been achieved in a VE. Behavioral data indicate that both translational and rotational body-based information are required to accurately update one's position during navigation, and participants who walked tended to avoid obstacles even though collision detection was not implemented and feedback not provided. A walking interface would bring immediate benefits to a number of VE applications.

Categories and Subject Descriptors: I.3.6 [Computer Graphics]: Methodology and Techniques - Interaction Techniques. I.3.6 [Computer Graphics]: Three-Dimensional Graphics and Realism - Virtual Reality. H.5.2 [Information Interfaces and Presentation]: User Interfaces - Input devices and strategies.
General Terms: Experimentation, Human Factors, Performance
Additional Key Words and Phrases: virtual reality, navigation, locomotion, visual fidelity

1. INTRODUCTION

When people navigate in the real world they use information from a number of distinct sources (principally visual and body-based) and several complementary cognitive processes. For example, movement may be perceived via optic flow (visual), proprioception and vestibular information (both body-based), and we can use path integration (body-based) and the proximity of a given landmark (usually visual) to determine where we have traveled within an environment [Foo et al. 2005; Loomis et al. 1999; Waller et al. 2004].

Three-dimensional virtual environments (VEs; virtual reality worlds) are capable of providing rich visual information, but there is strong evidence that visual information on its own is not sufficient if we are to navigate VEs as efficiently as we navigate in the real world. For example, in one study participants who learned a route through a virtual building made three times as many errors when asked to follow the same route in the real building than participants who both learned and were tested in the real building [Witmer 1996], in another study a navigational search task was performed perfectly in 93% of real-world trials versus only 55% of the trials conducted in a "photorealistic" VE [Lessels and Ruddle 2005], and a general finding is that more than a quarter of participants have great difficulty learning the layout of large virtual buildings that are presented in desktop VEs [Ruddle 2001].

Desktop VE interfaces (keyboard, mouse and/or joystick) provide little body-based information, but it's a different story with immersive VEs for which interfaces that involve physically turning, walking, walking-in-place and on treadmills have all been developed (e.g., [Darken et al. 1997; Hollerbach et al. 2003; Templeman et al. 1999; Whitton et al. 2005]).

The goal of the present study was to investigate how a walking interface affects people's ability to navigate, and to establish whether the provision of full body-based information allows VEs to be navigated with real-world ease. Both performance (expanding on preliminary data in [Ruddle and Lessels 2006]) and behavioral data

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(entirely new) are reported. First, however, we summarize research that has previously studied the effect of body-based information.

2. BODY-BASED INFORMATION

When considering body-based information, a distinction needs to be made between the rotational and translational components of movement. Historically, the rotational component has been considered much more important, because pointing between objects in a room was performed significantly more accurately when participants physically turned to face a starting orientation instead of imagining they had done so, but there was no significant difference between physical and imagined movement to a starting position [Presson and Montello 1994; Rieser 1989].

For VE navigation, the most common way of providing body-based information is to display the VE on a head-mounted display (HMD), and track a user's head movements to implement *gaze-directed* travel [Bowman et al. 2005]. Only occasionally has translational body-based information been provided in isolation (e.g., a linear treadmill), but a growing number of implementations are providing both components of body-based information, for example, through use of a physical walking interface.

Some studies have highlighted the benefits of providing a wide field of view (FOV), with path integration being performed accurately with just visual information in a VE that had a 180º FOV [Riecke et al. 2002] and objects being pointed to in the real world more accurately with an unrestricted FOV than when it was reduced to 40º × 30º [Riecke et al. 2004]. However, these findings did not apply to more complex spatial tasks such as navigational search, which participants performed in the real world with similar accuracy both with a normal FOV and when it was restricted to 20º × 16º [Lessels and Ruddle 2005].

2.1 Rotational information

Compared with visual information on its own, adding rotational body-based information provides significant benefits for a variety of basic spatial tasks. This manifests itself in terms of a significant improvement in accuracy when participants were asked to turn through a prescribed angle [Bakker et al. 1999], responding twice as consistently (measured in terms of angular error) when asked to point from one target to another than had been previously viewed [Lathrop and Kaiser 2002], performing path integration accurately in a head-tracked HMD but making large errors when only visual information was provided [Klatzky et al. 1998], looking around more while traveling [Ruddle et al. 1999], and performing a search task more accurately when carrying it out from a fixed location [Pausch et al. 1997].

The above studies show that rotational body-based information is important for basic spatial tasks, but this finding does not apply when complex tasks are conducted. Participants who used gaze-directed travel (rotational body-based information) to navigate an immersive VE did not develop significantly more accurate knowledge of a large-scale environment than when a desktop VE was used (visual information only), irrespective of whether that knowledge was assessed by direction estimates, distance estimates, or the distance participants traveled when wayfinding between locations [Chance et al. 1998; Ruddle and Péruch 2004]. In other words, rotational body-based information is not sufficient to solve the well-known difficulties people have navigating efficiently in large-scale VEs [Ruddle 2001].

2.2 Translational information

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VE interfaces that provide body-based information solely for the translational component of movement have been developed using walking-in-place algorithms and linear (one-direction) treadmills. The best-known device of this type is the Sarcos Treadport, for which a number of studies of detailed aspects of movement have been carried out, including maneuvering strategies [Vijayakar and Hollerbach 2002] and the use of force feedback to simulate walking up a slope [Hollerbach et al. 2003].

In studies of other basic spatial tasks participants who walked on a treadmill did not estimate the distance traveled any more accurately than participants who used a joystick to move [Witmer and Kline 1998], and when a treadmill was used in an architectural review application there were anecdotal reports of users becoming disoriented [Brooks et al. 1992]. The only study that showed a benefit of translational body-based information for large-scale navigation compared one-directional walking-in-place with joystick movement. After being guided along a route between eight exhibits in a virtual museum, participants were taken to the real museum and asked to find the exhibits in a different order. The joystick group traveled 18% further than participants who walked-in-place, who in turn traveled 17% further than a control group that was both trained and tested in the real museum [Grant and Magee 1998]. Thus, there is limited evidence that the translational component of body-based information is beneficial for navigation.

2.3 Translational and rotational information

The growth of wide area tracking technology has led to interfaces where a user physically walks around a large empty space that “contains” the virtual world and is provided with all of the body-based information we have when we navigate in the real world. Compared with gaze-directed travel (body-based information only for rotational movement), physical walking increased participants’ sense of presence [Usoh et al. 1999] and let them maneuver in a similar manner to real-world walking [Whitton et al. 2005] and helped participants to draw more accurate sketch maps after traveling around a virtual room [Zanbaka et al. 2005].

Few studies have investigated the effect of physical walking on the navigation of large-scale VEs but, compared with only visual information, walking did produce a small, significant improvement in accuracy when participants estimated the direction to objects that had been encountered while traversing a route [Chance et al. 1998].

Even the largest of current tracked spaces (e.g., the 20 x 30m of WorldViz’s PPTX8) is small compared with the environments we navigate on an everyday basis, which means that many applications would require an alternative to physical walking. For this, some researchers have evaluated hybrid interfaces that combine physical walking for local maneuverability with gaze-directed travel for movement over larger distances [Zanbaka et al. 2005]. Other researchers have proposed the use of devices like bi-directional treadmills [Darken et al. 1997; Iwata et al. 2005], but these are not yet suitable for real applications [Bowman et al. 2004].

The limitations of bi-directional treadmills have led several groups to develop algorithms that allow users to travel through virtual worlds by walking-in-place. The most sophisticated of these allows fine-grained control of movement [Templeman et al. 1999], and another increased participants’ sense of presence when compared with gaze-directed travel [Slater et al. 1995; Usoh et al. 1999]. Generally, however, all current walking-in-place algorithms have certain quirks [Whitton et al. 2005], meaning that they make travel more realistic than gaze-directed techniques, but less so than physical walking.

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3. OVERVIEW OF THE EXPERIMENTS

While physical walking and walking-in-place interfaces undoubtedly allow users to travel around environments in a fairly realistic manner, we still cannot explain:

a) Why do users find it so much harder to navigate in VEs than the real world, and

b) What can we do about it?

We addressed these questions by asking participants to travel around a room-sized space, searching for eight targets that were randomly placed in 16 explicitly identified, possible locations. If a participant checked each location once then they were guaranteed to be successful (a *perfect search*), but to do this they had to integrate information seen from multiple positions and remember where they had traveled.

Each participant navigated the virtual room by: (a) gaze-directed travel and a desktop display, (b) gaze-directed travel and an HMD, or (c) physically walking around the room while viewing it on an HMD. These groups differed in terms of the type of body-based information with which they were provided (none vs. rotation vs. translation and rotation), and were termed *visual-only*, *rotate* and *walk*, respectively.

In Experiment 1 participants performed the task in a detailed virtual model of our laboratory, and in Experiment 2 a simple ("impoverished") model was used. This allowed us to determine whether a real-world level of performance could be attained irrespective of the amount of visual detail the environment contained.

The next two sections report each experiment, but to ease comparison the results for both experiments are combined into the same figures (e.g., Figure 2). This is followed by a section that analyzed the participants' search paths in the study as a whole, and a general discussion.

4. EXPERIMENT 1

4.1 Method

4.1.1 Participants

Thirty individuals (16 men; 14 women) with a mean age of 24 years (*SD* = 3.4) took part. A between participants design was used, with 10 participants randomly assigned to each group (visual-only, rotate and walk). All the participants gave informed consent and were paid an honorarium for their participation. The study was approved by the Ethics Committee in the Faculty of Engineering, University of Leeds.

4.1.2 Materials

The virtual model was constructed using measurements of the laboratory's geometry (see Figure 1a) and photographs of the interior. Added to the model were 33 identical cylinders, all 0.15m diameter and 1.35m high, and 16 identical boxes (see Figure 1b). The cylinders were arranged in eight blocks of four, with the 33rd cylinder being central (see Figure 1a). In each trial, the boxes were placed on top of cylinders chosen at random, subject to the constraint that one cylinder in each block was a target and another a decoy (this ensured that the targets and decoys were distributed around the environment).

In each trial, participants were asked to travel around the model until they had found the eight targets, pressing either a button on a 3D mouse (walk and rotate groups) or a key on a keyboard (visual-only group) to raise/lower a box's lid to see whether a target was inside. The virtual world software, written using OpenPerformer, prevented more than one box lid from being raised at any given moment in time. Another

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button/key was pressed to indicate a target had been found, causing it to turn blue. The model was rendered by an SGI Onyx4 graphics workstation at 60 frames/sec., with overall system latency of approximately 50 ms.

Participants in the walk group physically walked around the laboratory while viewing the corresponding virtual model in stereo on a Virtual Research V8 HMD (48º × 36º FOV; 100% binocular overlap; see Figure 1d). The position and orientation of a participant's head was tracked in six degrees of freedom using a WorldViz PPT and an Intersense InertiaCube2.

Participants in the rotate group stood in one place and viewed the virtual world in stereo on the HMD. They achieved movement by physically rotating, tracked by the InertiaCube2, but holding down a button on the 3D mouse to translate at a speed of 1 m/s.

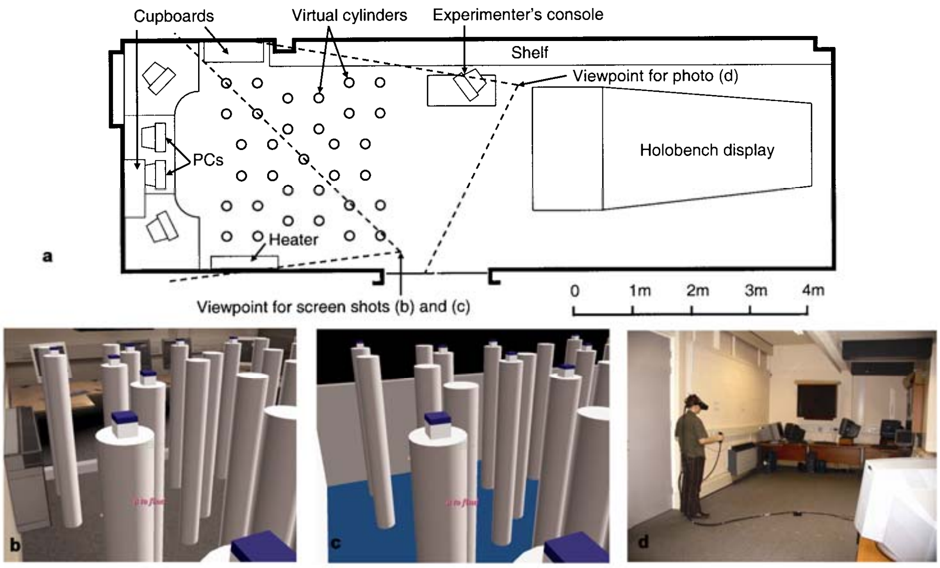

Fig. 1. Experimental setup: (a) Plan view of the physical laboratory, showing location of the virtual cylinders, (b) Visually detailed virtual model used in Experiment 1, which contained all the furniture, computers, etc. that was present in the actual laboratory, (c) Visually impoverished model used in Experiment 2,which contained nothing except the cylinders, boxes, targets and four gray walls, and (d) Person standing in the position used to generate views (b) and (c), wearing the HMD.

Participants in the visual-only group looked at a non-stereo view of the virtual world. This was presented on a 21-inch monitor, and the graphical field of view (48º × 39º) was similar to the angle subtended by the monitor from a normal viewing distance (600mm). When participants held down the 'up' cursor they traveled at a speed of 1 m/s in the direction they were looking. View direction was controlled using the mouse, with the pitch directly proportional to the vertical offset of the cursor from the center of the screen (up to +/- 90 degrees), and heading changing at a rate that was proportional to the horizontal offset of the cursor from the screen's center (maximum rate of turning = 135 degrees/sec.).

For all three groups the virtual eye height was initialized to 1.65m, ensuring everyone could see over the top of the cylinders. Participants were prevented from moving outside the virtual room by either a collision detection algorithm that slipped them along its walls (rotate and visual-only groups) or the room's physical walls (walk group). In all three groups, participants were free to travel through the cylinders. The walk and rotate groups were provided with a stereo view because that is the way that HMDs are typically used, whereas desktop displays are generally used in non-stereo mode.

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4.1.3 Procedure

Each participant in the visual-only group performed four practice trials to allow familiarization with the interface controls and search task, and then performed four test trials. Participants in the walk and rotate groups did two practice trials using the same system as the visual-only group, and then two more practice trials and the four test trials using the type of movement relevant to their group (walk or rotate). This allowed participants' initial familiarization with the task to take place while sitting in front of a monitor, rather than wearing an HMD that obscured the experimenter.

Participants were informed that the targets were always in the boxes, but that their positions changed between trials. They were asked to complete the task as efficiently as possible, not checking each box more than once. No feedback was provided on participants' performance or their search strategy.

On average, each participant took one hour to complete the experiment. Participants who used the HMD took a short break after each HMD trial and, at the end of the experiment, were monitored were monitored for an additional hour using the *Short Symptoms Checklist* [Cobb et al. 1999], as a standard precaution against virtual environment sickness. Only minor symptoms occurred.

4.2 Results and discussion

In each trial, a participant's performance was categorized as either perfect or imperfect. A perfect search was one in which each target/decoy was only checked once (participants had no prior knowledge of which boxes contained targets, but checking each box once guaranteed success), whereas imperfect searches were those in which at least one target or decoy was re-checked. To analyze the effect that different navigation interfaces had on participants' ability to avoid obstacles, the rate at which participants collided with the cylinders was calculated.

Initial analyses showed no significant change in performance or collisions across the test trials. Therefore, the data were averaged across trials, and analyzed using two factor (movement x gender) between participants analyses of variance (ANOVAs). A Type III Sums of Squares calculation was used, which is appropriate for an unbalanced design (due to the random assignment of participants to groups, there were five men in the rotate and visual-only groups, but six in the walk group). There were no significant interactions between movement and gender.

4.2.1 Search performance

The walk group performed many more perfect searches than the rotate and visual-only groups (see Figure 2), and an ANOVA showed significant effects of movement, $F(2, 24) = 10.11$, $p < .01$, and gender, $F(1, 24) = 4.26$, $p < .05$. Bonferroni post-hoc tests showed that participants who walked performed significantly more perfect searches than participants in the rotate and visual-only groups ($p < .01$, in both cases), these latter two groups being equivalent.

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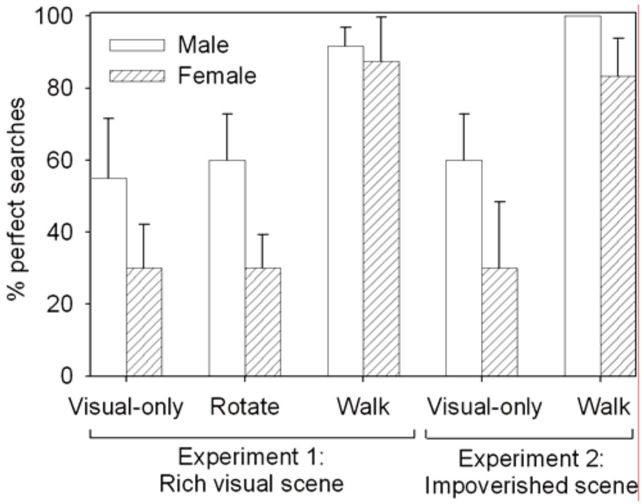

Fig. 2. Mean percentage of perfect searches made by participants. Error bars indicate the standard error.

To quantify the search efficiency of each trial, a participant's path was approximated by straight line segments between the start point and the center of targets/decoys each time one was checked, and compared with the shortest possible path that visited all 16 targets/decoys. The shortest path was calculated using an exhaustive traveling salesperson algorithm, which was written by the authors and calculated paths that ended at the 16th target/decoy, unlike traditional versions of the algorithm which calculate paths that start and finish at the same place. Participants in the walk condition traveled an average of 7% further than the shortest path, whereas participants in the rotate and visual-only conditions traveled 32% and 46% further, respectively.

On trials that were not performed perfectly, there were large performance variations (see Table I). Participants in the walk group only ever made small errors, either re-checking one box (3 trials) or three boxes (1 trial). By contrast, participants in the rotate and visual-only groups rechecked at least a quarter (four or more) of the boxes in 20% and 22.5% of trials, respectively. The difference between a typical trial and the worst trial for each group is shown in Figure 3. On the worst trial of all (the top right image in Figure 3), the participant concerned checked every box an average of four times before finding the final target!

Group	Visual Scene	Number of targets/decoys re-checked															
		0*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Walk	Rich	36	3		1												
	Impoverished	36	1	2		1											
Rotate	Rich	18	10	3	1	1	2	1	1			1		1		1	
Visual-only	Rich	17	7	2	5	1	1	1	2				2		1		1
	Impoverished	18	2	2	1	1	2		3			2	3		1	3	2

Table I. Number of trials in which a given number of targets/decoys were re-checked (*0 = perfect search; one or more targets/decoys = imperfect search). Experiment 1 used the rich scene, and Experiment 2 the impoverished one.

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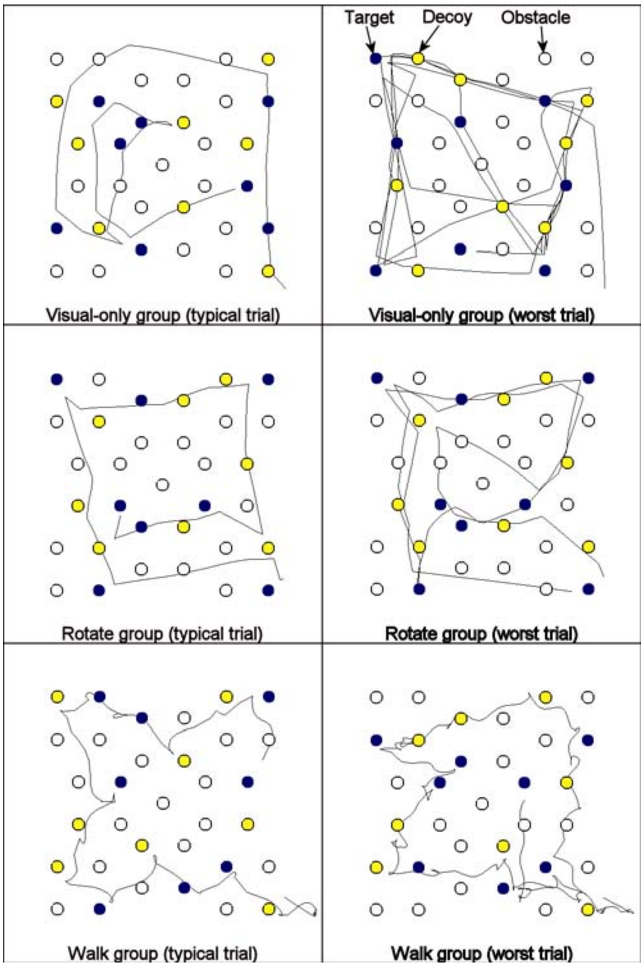

Fig. 3. Paths followed by participants during a typical (median performance in terms of the number of targets/decoys that were re-checked) and the worst trial for each group in Experiment 1.

These results show that walking had a dramatic effect. The walk group performed comparably to participants in another study who took part in a similar task in the real world (90% trials perfect) [Lessels and Ruddle 2005]. By contrast, when translational body-based information was not provided (the rotate group) performance was similar to when participants had to search using just visual information. The results for these two groups also indicate that the provision of a stereo view had no effect on performance.

Men often outperform women in spatial tasks (see [Waller 2000]). This was certainly true of our rotate and visual-only groups, but when participants walked the gender difference was minimal. This narrowing of gender differences has also been observed when participants were provided with a wide field of view [Czerwinski et al. 2002].

4.2.2 Obstacle avoidance

Inspection of participants' paths (see Figure 3) shows that the walk group tended to travel around cylinders, but the other groups through them. For each trial, we calculated the collision rate as the number of times the path intersected a cylinder, divided by the distance traveled (clearly, longer paths would have more intersections). To calculate the distance, jitter caused by sensor noise in the walk group's position data was removed using two passes of a low pass Butterworth filter [Winter 1990].

The walk group collided less than half as often as the rotate and visual-only groups (see Figure 4). An ANOVA showed a main effect of movement, $F(2, 24) = 24.13$, $p < .001$, and Bonferroni post-hoc tests showed that the difference between the walk group and each of the other groups was significant ($p < .001$, in both cases). There was no effect of gender, $F(1, 24) = 2.28$, $p > .05$.

In other words, the walking interface helped participants to avoid obstacles, even though no collision detection or feedback was provided. This is the first time such behavioral differences have been quantified, and supports anecdotal observations made in earlier studies [Witmer et al. 2002; Zanbaka et al. 2005].

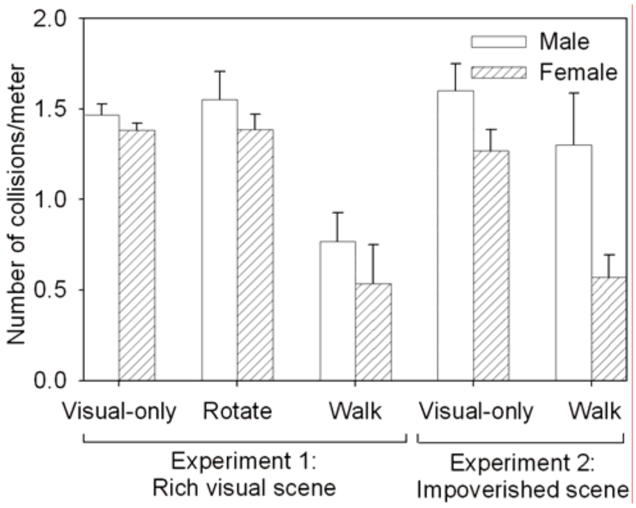

Fig. 4. Mean number of collisions with cylinders per meter traveled. Error bars indicate the standard error.

5. EXPERIMENT 2

The visual environment used in the first experiment contained many salient surrounding features (e.g., door, cupboards and computers; see Figure 1) that may have helped participants maintain their orientation and, therefore, identify the parts of the environment that had (not) been searched. To investigate whether participants can only navigate efficiently if both rich visual information and full body-based information are provided, we conducted a second experiment using an impoverished virtual model.

5.1 Method

5.1.1 Participants

Twenty new participants (8 men; 12 women) with a mean age of 22 years ($SD = 4.0$) were recruited and randomly assigned to two groups. Half of these participants walked around the impoverished virtual model (walk group) and the others moved using mouse and keyboard (visual-only group). A rotate group was not used because, in Experiment 1, performance of the rotate and visual-only groups was similar.

5.1.2 Materials and procedure

The impoverished model just contained the cylinders, boxes, targets and four gray walls (see Figure 1c), and provided far less visual information for a participant to use. The procedure was the same as for Experiment 1.

5.2 Results and Discussion

Initial analyses of the data showed no effect of trial number so, as in Experiment 1, the data were averaged across trials for the analyses presented below. Due to the random assignment of participants to groups, there

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were five men in the visual-only group and four in the walk group. However, the Type III Sums of Squares calculation that was used is appropriate for an unbalanced design.

A two factor (movement x gender) ANOVA showed that the walk group performed significantly more perfect searches than the visual-only group, $F(1, 16) = 12.80$, $p < .005$, but the difference between men and women was not significant, $F(1, 16) = 3.20$, $p > .05$ (see Figure 2).

Another ANOVA (movement x gender x visual scene) compared the performance of the walk and visual-only groups in the two experiments. There was no significant difference between the rich and impoverished visual scenes, $F(1, 32) = 0.07$, $p > .05$, but men performed significantly more perfect searches than woman, $F(1, 32) = 4.59$, $p < .05$, and as expected participants who walked performed significantly more perfect searches than the participants in the visual-only groups, $F(1, 32) = 28.07$, $p < .001$.

As in Experiment 1, search efficiency was quantified by comparing participants' paths with the shortest possible path, calculated using a traveling salesperson algorithm. Participants in the walk condition traveled an average of 16% further than the shortest path, compared with 69% further for the visual-only condition.

In terms of obstacle avoidance in Experiment 2, an ANOVA showed that the walk group collided with cylinders significantly less often than the visual-only group, $F(1, 16) = 8.95$, $p < .01$, and women collided less often than men, $F(1, 16) = 10.21$, $p < .01$. Men in the walk group collided twice as often as in Experiment 1 (see Figure 4).

Participants' performance was largely unaffected by the amount of detail in the visual scene, indicating that full body-based information is necessary for efficient navigation, but a rich visual scene is not. The increased rate of collisions of male walkers in Experiment 2 deserves further study.

6. SEARCH PATHS

In both experiments, the performance of participants in the walk group was, by far, superior to that of participants in the other groups. To understand why, the paths that participants followed in the two experiments were analyzed together at three levels of detail.

First, adopting a method used in previous research (determining the order in which each quadrant of the environment was visited; Lessels & Ruddle, 2005) participants' general strategy was classified as: (a) perimeter (participants initially checked the targets/decoys around the perimeter of the environment, and then checked those that were in the center), (b) lawnmower (searching in a series of parallel lanes), or (c) other (2% of trials didn't involving any single clear strategy). A perimeter strategy was dominant, irrespective of participants' group or search performance. In the walk groups, 79% of perfect searches involved perimeter strategy. In the rotate and visual-only groups, a perimeter strategy was used for 68% perfect searches and 67% of the most inefficient searches (those in which at least half the targets/decoys were re-checked).

The environment contained eight blocks of four cylinders and, in each trial, one cylinder in each block was a target and another was a decoy (see section 4.1.2). The second analysis just involved trials that had used a perimeter strategy, and compared participants' paths at the level of detail of the blocks. Each path was expressed as a sequence of blocks (see Figure 5), and measures such as the sequence length, number of occurrences of each sequence, and mean edit distance (mean number of operations required to change a given sequence into each of the other sequences; Levenshtein 1966) were calculated.

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In perfect searches, the particular sequence that occurred most often (21 times) was {1,2,3,4,5,6,7,8} (see Figure 5a). This was also the sequence that was the closest match to all the others (mean edit distance = 1.7), although the mean length of the perfect search sequences was 9.0 blocks (*SD* = 1.0). In other words, a typical perfect search involved checking seven blocks once and one block twice (the block's decoy on one occasion and its target on the other), and an example of such a path is shown in Figure 5b.

The most inefficient searches (at least half the targets/decoys re-checked) had a mean sequence length of 22.3 blocks (*SD* = 5.7), of which 7.1 blocks were visited before the first target/decoy was revisited. This was indicative of participants returning to one part of the environment before checking all the others, and an example in which Block 2 was initially neglected is shown in Figure 5c.

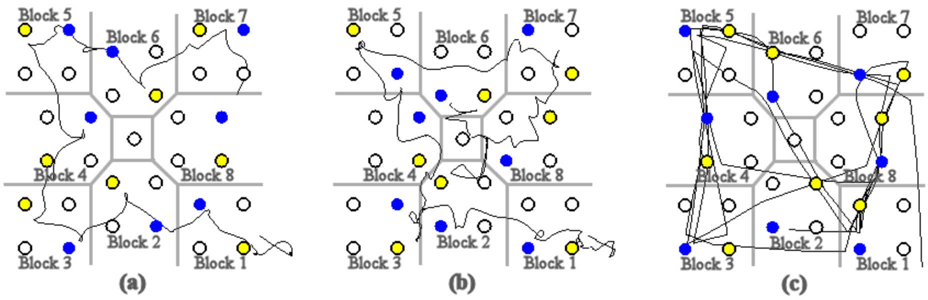

Fig. 5. Sequences in which targets (blue) and decoys (yellow) in each block were checked: (a) Sequence that occurred most often in perfect searches {1,2,3,4,5,6,7,8}, (b) Perfect search sequence of average length (9 blocks; {1,2,3,4,5,7,8,2,6}), and (c) Inefficient search that checked targets/decoys in seven blocks (underlined in the following sequence) before revisiting a target/decoy and the finding the remaining targets (full sequence {7,6,5,4,3,1,8,7,8,1,2,6,5,4,3,2,8,7,6,5,4,3,4,5,6,2,1,8,1,8,2,4,5,6,7,8,1,2}).

The third and finest level of detail for the path analysis focused on what happened during the initial part of participants' searches. Each trial was divided into its *primary phase* (the path traveled until any target or decoy box was checked twice; for perfect searches this was the whole of the trial) and its *secondary phase* (all subsequent movements). Then, for every target that was not found during the primary phase, we determined whether the participant had either already traveled past it (a *miss*) or *neglected* to visit its locality, defined using Delaunay triangulation (see Figure 6). Defining the locality in this way meant that misses referred to situations where a given target should have been checked because nothing lay between it and the participant, whereas in neglect a participant would have had to move past other cylinders to reach the target.

The majority of errors were neglect (see Figure 7), with misses only being a secondary cause of the performance differences we observed. The visual-only group made many more misses than either of the other groups, who either never (walk group) or hardly ever (rotate group) missed a target. Participants in both these latter groups were able to make quick sideways glances during navigation simply by turning their head (rotational agility), as has previously been found during the navigation of virtual buildings [Ruddle et al. 1999].

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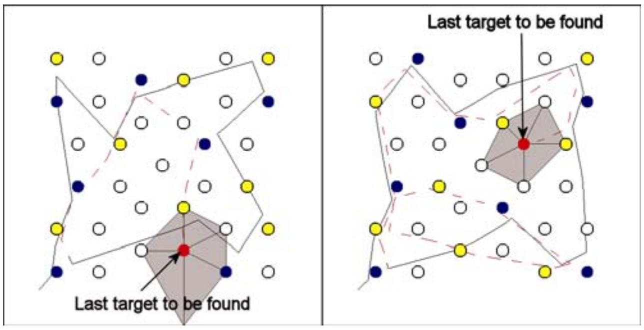

Fig. 6. Examples of a miss (left) and neglect (right). The shaded region shows the last target's locality. Path followed in primary phase is a solid line, and secondary phase is dashed.

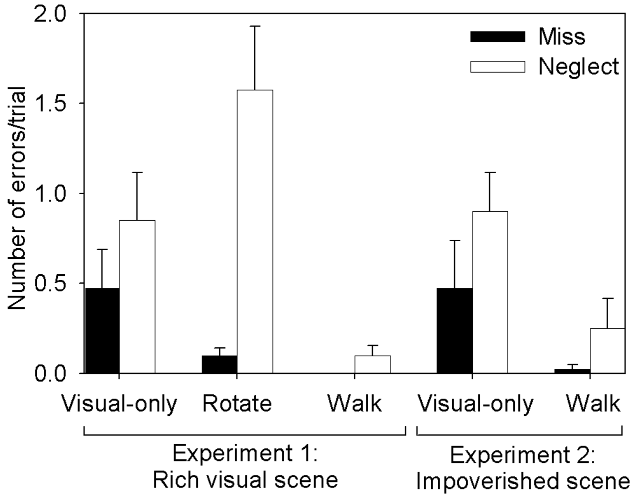

Fig. 7. Mean number of miss and neglect errors in each trial. Error bars indicate the standard error.

7. GENERAL DISCUSSION

This study set out to answer two questions: (1)Why do users find navigation so much harder in virtual worlds than the real world, and (2) How should we apply what we have learned to VE applications? Answers to these are discussed in the following sections.

7.1 Why is it difficult to navigate in virtual worlds?

Studies into this question have focused on three factors: environment fidelity, the FOV, and movement fidelity [Waller et al. 1998]. Environment fidelity mostly relates to the quantity of visual detail that is contained within a VE model and, although high-fidelity environments may be required for aesthetic purposes (e.g., in computer games), research has consistently shown that the addition of landmarks or rich visual scenes produces, at best, only a modest improvement in navigational performance [Ruddle et al. 1997; Ruddle 2005; Steck and Mallot 2000]. The results of the present study add further weight to this conclusion.

A wide FOV has been shown to improve performance in basic spatial tasks such as path integration [Riecke et al. 2002], and narrow FOVs affect one's perception of a space [Alfano and Michel 1990]. However, like environment fidelity, a wide FOV has only a modest effect when more complex tasks such as navigational search are conducted in VEs [Lessels and Ruddle 2004; Ruddle and Jones 2001].

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In contrast to the other two factors, body-based information (i.e., movement fidelity) makes a large difference to performance in both basic tasks [Bakker et al. 1999; Klatzky et al. 1998] and the present study's task of navigational search. This is reinforced by brain imaging studies of rats which showed how the firing of hippocampus place cells was affected by motor input (for a review of research in this area, see [Brotons-Mas et al. 2006]).

In the present study both translational and rotational body-based information (the walk group) were required for efficient navigation. If only the rotational component was provided (the rotate group), or neither component (the visual-only group), then the process of remembering where one had traveled became much more error-prone, and this was largely unaffected by whether a rich or impoverished visual scene is provided. The path analysis showed that the overall strategy that participants adopted (perimeter vs. lawnmower) did not affect performance, but differences were apparent when the path data were analyzed at finer levels of detail. This led us to hypothesize that the walk group performed more perfect searches because:

a) Walking increased participants' agility, which made it easier to deviate to targets and decoys (it is well known that small time differences in interaction cost can have a large impact on performance [Gray and Fu 2001]), or
b) It was only when translational and rotational body-based information was provided that participants could accurately remember where they had (not) traveled (spatial updating [Loomis et al. 1999]).

The dominance of neglect errors indicates that spatial updating (hypothesis (b)) was the main cause of the performance differences we observed. Within this, the large difference between the walk and rotate groups in Experiment 1 highlighted the critical role that the translational component of movement plays in the process of updating one's location during navigation.

7.2 Harnessing body-based information in VE applications

Our study involved, by far, the most complex navigational task to date in which a real-world level of performance has been achieved in a VE, and so is a notable step toward the creation of environments that in terms of usability represent a virtual "reality". For some applications, users would derive immediate benefits from a walking interface identical to the one used in our study because the spaces involved are small enough to be tracked at 1:1 scale by current technology. Examples of suitable applications include design of the layout of control rooms or manufacturing cells in a factory. These often involve cluttered spaces and it should be emphasized that, as shown by our behavioral data, a walking interface made it easy for participants to maneuver around obstacles even though collision detection was not implemented and participants' eye point was higher than the top of the obstacles so there was never any feedback when a collision took place (e.g., a visual discontinuity caused by the eye passing through an obstacle).

In other applications (e.g., architectural design, training for emergency evacuation, and virtual tourism) users need to navigate large environments such as buildings or cities. Clearly this is different to navigating a room, but there are notable parallels in: (a) the large minority of participants who have difficulty navigating (30+ % in large-scale spaces [Ruddle 2001] vs. 20+ % of trials in the present study), and (b) participants' tendency in both large-scale and room-sized spaces to repeatedly search certain parts while leaving others untouched. Further research is required in two distinct areas.

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First, we need to determine whether the navigational benefits produced by actual walking also apply to interfaces such as walking-in-place [Slater et al. 1995; Templeman et al. 1999; Whitton et al. 2005] and treadmills [Darken et al. 1997; De Luca et al 2007; Hollerbach et al. 2003; Iwata et al. 2005]. These provide body-based information from a proprioceptive source (muscle movement) for the translational and rotational components of movement, but from a vestibular source (balance system) only for the rotational component. The proprioceptive source is essential for optimal performance in basic spatial tasks [Bakker et al. 1999; Peruch et al. 2005] but the contribution made by the vestibular source remains an open question. Although low-level aspects of movement have been studied using walking-in-place and treadmill interfaces (e.g., [Hollerbach et al. 2003; Pelah and Koenderink 2007; Whitton et al. 2005]), the effect on large-scale navigation remains unknown.

Second, if interfaces such as walking-in-place and treadmills do allow a real-world level of navigational performance to be achieved in VEs then research is needed to determine whether navigation is impaired if the interfaces are then adapted to allow the use of displays that only partly surround a user (e.g., three-sided CAVE or 180º curved projection screen), for example, by the implementation of a redirected walking technique [Razzaque et al. 2002].

Finally, men outperformed women in our study, but the magnitude of this difference was much smaller for the walk group than the other groups. Modern VE applications have a diverse user population, so interaction techniques that narrow performance differences between individuals are to be welcomed.

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http://doi.acm.org/10.1145/1502800.1502805.

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Basic search performance data (percentage of perfect searches and number of targets/decoys that were checked twice or more) for these experiments were reported in Ruddle and Lessels [2006]. However, the majority of the data in the present paper are previously unpublished, and this includes the comparison of participants' searches against the shortest possible path, the data about obstacle avoidance, and the Search Paths section that analyzed participants' paths at three levels of detail. The new data provide an explanation for the large performance differences that occurred in the experiments, which is critical if we are to understand why full body-based information makes such a difference to navigation, and help us to draw conclusions about the qualitative changes that walking interfaces bring to VE navigation which is important if VE technology is to be successfully successful applied.

This research was supported by grant GR/R55818/01 from the Engineering and Physical Sciences Research Council.
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