Leveraging Change Blindness for Redirection in Virtual Environments

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Abstract

We present change blindness redirection, a novel technique for allowing the user to walk through an immersive virtual environment that is considerably larger than the available physical workspace. In contrast to previous redirection techniques, this approach, based on a dynamic environment model, does not introduce any visual-vestibular conflicts from manipulating the mapping between physical and virtual motions, nor does it require breaking presence to stop and explicitly reorient the user. We conducted two user studies to evaluate the effectiveness of the change blindness illusion when exploring a virtual environment that was an order of magnitude larger than the physical walking space. Despite the dynamically changing environment, participants were able to draw coherent sketch maps of the environment structure, and pointing task results indicated that they were able to maintain their spatial orientation within the virtual world. Only one out of 77 participants across both both studies definitively noticed that a scene change had occurred, suggesting that change blindness redirection provides a remarkably compelling illusion. Secondary findings revealed that a wide field-of-view increases pointing accuracy and that experienced gamers reported greater sense of presence than those with little or no experience with 3D video games.

Index Terms: H.5.1 [[Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

Keywords: virtual environments, redirection, change blindness

1 Introduction

Real walking has been shown to provide advantages over common alternative locomotion techniques in immersive virtual environments, including a greater sense of presence [28], more efficient travel [25], superior performance on search tasks [20], and benefits for memory and cognition [24] [34] . While advances in wide-area tracking technology have made it possible to accurately capture users' motions over room-sized areas, the walkable area in a virtual environment is ultimately restricted by the size of the physical workspace. To overcome this size limitation while maintaining a natural walking interface, a variety of *redirection* techniques have been proposed to imperceptibly decouple the user's locations in the physical and virtual worlds.

In this paper, we present a novel redirection technique that exploits *change blindness*, a perceptual phenomenon that occurs when a person fails to detect a visual change to an object or scene [14]. By applying manipulations to the model of the virtual world, we demonstrate that a user can seamlessly walk through a virtual environment that is an order of magnitude larger than the physical workspace. In contrast to previous redirection techniques, our approach, based on a dynamic, adaptive environment model, does not introduce any visual-vestibular conflicts from manipulating the mapping between physical and virtual motions, nor does it require breaking presence to stop and explicitly reorient the user. However, it does impose a different set of constraints with regards to environment geometry and user motion. To evaluate this technique, we developed a proof-of-concept virtual environment and performed two user studies to measure the effectiveness of the change blindness illusion.

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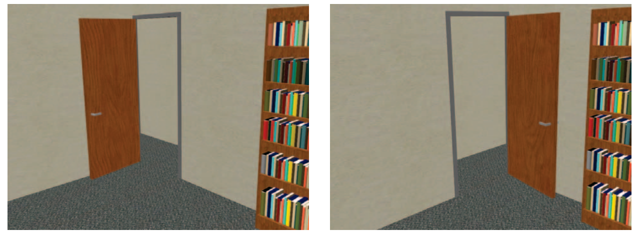


(a) Before Scene Change (b) After Scene Change

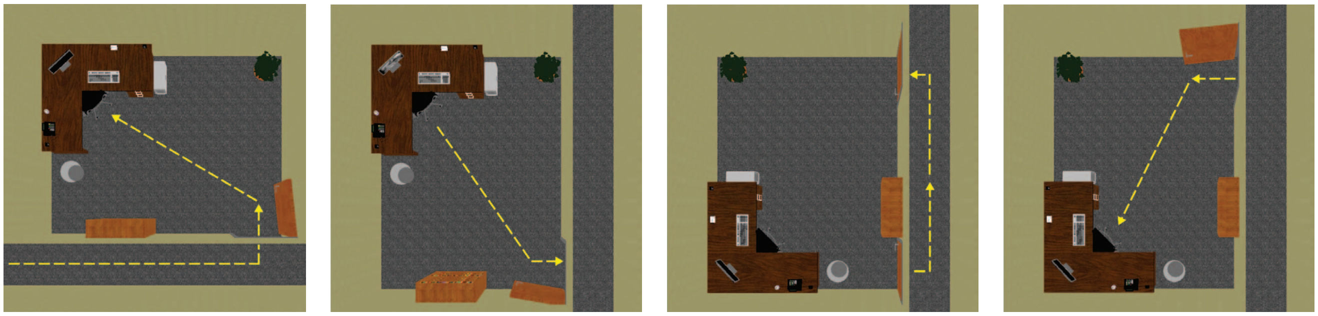
Figure 1: An example of a scene change in which a doorway and the adjoining corridor are instantly rotated by 90 degrees when the users look away. Users exiting the room will proceed down the hallway in a different direction than when they entered.

2 Previous Work

Two general approaches to redirection have been proposed in the literature: (1) manipulating the mapping between physical and virtual rotations to orient the user away from the boundaries of the physical workspace, and (2) scaling physical movements to enable travel over greater distances in the virtual world. Both of these techniques introduce a visual-vestibular conflict; however, research in perceptual psychology has shown that vision generally dominates when these cues conflict [13] [15].

Redirected walking is a technique that introduces a rotational gain in order to imperciptibly rotate the user away from the boundaries of the tracking space [19]. In the context of virtual environments, several recent psychophysical studies have been conducted to examine the thresholds for detecting rotational manipulation under different conditions, such as during head turns [9], during body turns [5], or during walking [7]. Results from a study of several techniques have shown that users can be physically turned approximately 49% more or 20% less than the perceived virtual rotation without noticing and can walk along a circular arc with a radius of at least 72 feet while believing that they are walking in a straight line [23].

Scaled translational gain techniques manipulate the user's translations instead of rotations. This technique can be implemented most simply by applying a uniform scale factor so that any movement in the real world covers a greater distance in the virtual environment [31]. Noting that a uniform scale factor exaggerates the oscillatory head sway associated with natural walking, Interrante et



(a) The user enters a 14’ x 11’ room and walks towards a desk to view the computer monitor.

(b) When the user approaches the monitor, the corridor and the door to exit the room are instantaneously rotated by 90 degrees.

(c) When the user enters the hallway, the second doorway is added, and the contents of the room are swapped with the next room.

(d) The first door is removed as the user enters the second room. The process can then be repeated.

Figure 2: A step-by-step explanation of our proof-of-concept implementation of change blindness redirection. Dynamic modifications to the virtual environment model prevent users from walking outside the boundaries of the 14’ x 14’ workspace as they transition between two rooms in the virtual world. This process can be repeated indefinitely to enable walking through a large virtual environment with an arbitrary number of rooms.

al. improved this approach by estimating the user’s intended direction of travel and scaling only the motion aligned with that direction [8]. In a psychophysical study, Steinicke et al. found that distances could be downscaled by 14% or upscaled by 26% without being noticeable to the user [23]. Additionally, scaled translational gains can be combined with rotational gains, such as the interface developed by Bruder et al., which also introduced the concept of virtual portals to allow large immersive architectural walkthroughs [4].

While redirection techniques can be applied continuously as the user walks around, another common approach is to stop and reorient the user only at the boundary of the tracking area, a technique known as resetting [32]. While reorientation is typically achieved by rotational gains, a recent study has shown that this approach can also be combined with scaled translational gain techniques [33]. However, a notable disadvantage of resetting is that it requires interrupting the user. To mitigate these potential breaks in presence, Peck et al. suggested introducing distractors for the user to focus on during reorientation, and showed that they were preferred over visual or audio instructions [16]. Furthermore, they also demonstrated that reorientation with distractors allows users to perform no worse on pointing and sketch map tests than real walking [17].

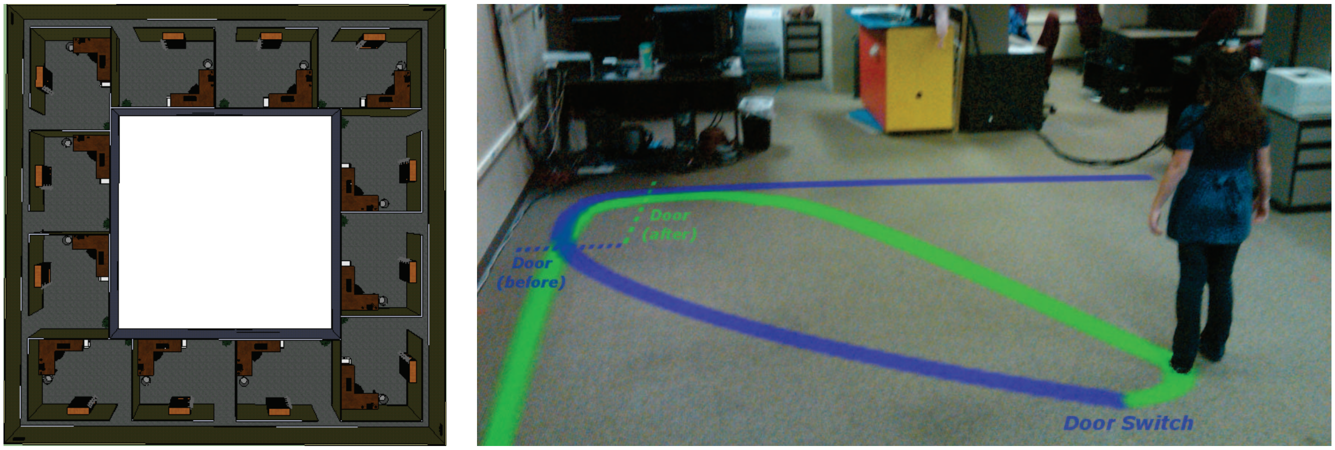
In contrast to previous redirection techniques, our method does not continuously manipulate the mapping between physical and virtual motions, thereby avoiding a visual-vestibular conflict. Furthermore, it does not introduce any breaks in presence from resetting the user. Instead, we suggest an alternative approach - *instead of manipulating the user’s motion to fit the environment, we manipulate the environment to generate the motions we want the user to take*. Our technique leverages the human visual system’s natural insensitivity to scene changes, a perceptual phenomenon that has also previously been exploited to reduce graphical rendering times without compromising perceived visual quality [6]. Wallis et al. showed that change blindness also occurs in dynamic virtual environments, and that observer movement reduces the detection of scene changes [30]. In a recent study, Steinicke et al. showed that change blindness phenomena occur with the same magnitude in monoscopic and stereoscopic viewing conditions, and explored flicker techniques for introducing scene changes in stereoscopic scenes [22]. Additionally, in a study using a head-mounted display instrumented with an eye tracker, it has been demonstrated that scene changes can be inserted during a saccade, making them difficult to detect [27].

3 Change Blindness Redirection

A variety of processing strategies for dealing with conflicting visual information have been suggested to explain change blindness, such as: (1) people will rely on their first impressions of an environment, (2) their initial mental representation will be overwritten, and (3) conflicting features will be combined [21]. Whichever strategy is used, many experiments have shown that if a person’s visual field is occluded during a scene change, it is very difficult to notice that a change has occurred after their vision is restored [3]. Perceptually, the human visual system relies heavily upon transient optical motion to update the internal visual representation of a scene [18]. However, when transient optical motion information is not available, top-down processing strategies are often used, where the person’s concepts, expectations, and memories influence the recognition of the scene [14]. In the context of a virtual environment, as long as scene manipulations occur outside the user’s field-of-view, we suggest that these manipulations will be difficult to detect due to the reliance on these top-down processing strategies. To exploit this phenomenon, we developed a technique known as *change blindness redirection*, which redirects the user’s walking path through subtle manipulation to the geometry of the virtual environment model. Since building architecture does not spontaneously change in the real world, we believe that users will unconsciously assume that the architectural layout of the virtual world is fixed.

Figure 1 shows an example of a scene change that can be used to redirect the user’s walking path in a virtual environment, which is based upon manipulating the orientation of doorways behind the user’s back. When a doorway is instantaneously rotated, the adjoining corridor is also realigned, causing users to walk down the virtual hallway in a different direction than when they entered the room. These ”doorway switches” can be repeatedly applied to allow the user to explore a seemingly large virtual environment while walking within a relatively small square in the physical workspace. Figure 2 demonstrates the step-by-step manipulations that are applied as the user walks between two rooms. This process can be repeated an arbitrary number of times to give the impression of an expansive virtual space with hallways that are much longer than the dimensions of the physical workspace.

To evaluate the effectiveness of the change blindness redirection technique, we extended our proof-of-concept example to create a dynamic virtual office building with 60’ long hallways and a total of 12 rooms spread over 2352 sq. feet of walkable space. Utilizing the demonstrated method, the user can seamlessly walk through the



(a) Virtual World - 60’ x 60’

(b) Real World - 14’ x 14’

Figure 3: (a) The virtual office building comprised 12 rooms over 2352 sq. feet of virtual space. (b) In the real world, the user walked within a 14’ x 14’ area. The user’s path traveling down the hallway and entering a room prior to the scene change is shown in blue. The path exiting the room after the scene change and continuing down the hallway is shown in green. Each virtual hallway corresponds to one complete revolution about the outside perimeter of the tracking space.

environment while physically remaining inside a 14’ x 14’ tracking area (see Figure 3). The scene change is triggered when a participant approaches the desk located in each office. Exploring the entire office requires the scene change to be applied once per room, for a total of 12 times. To ensure that users are looking away from the door when the scene change is applied, a computer monitor on a desk activates based on the user’s proximity and displays a picture to the user. For the purposes of our studies, turning on the computer screens also serves as the experimental task that participants were told to perform. This virtual environment was used to perform all the experiments described in this paper.

The environment is designed to be explored by visiting each room in order. It should be noted that our implementation of the redirection technique fails if the user skips visiting a room and continues walking down the entire length of the hallway. While this limitation imposes restrictions on the user’s exploration, it allows more local freedom of movement within a limited space than redirected walking, which also assumes the user follows a particular path [19]. Additionally, our implementation adjusts the room dimensions during the scene change to make space for the shifting position of the hallway (14’ x 11’ to 11’ x 14’). We did this to maximize the walking space within the our limited tracking area. However, this aspect ratio adjustment is not a requirement of the technique, and the room dimensions could be kept constant with a larger tracking area.

4 Experiment 1: Initial Study

Our first experiment was designed to evaluate the change blindness redirection technique to determine (1) how well users are able to notice the scene changes and (2) whether they are able to form a coherent mental map of the dynamic virtual environment. We also investigated whether it is necessary to distract users to make them less sensitive to scene changes. To probe this issue, we varied the inclusion of a working memory task as an independent variable.

4.1 Participants

A total of 37 people participated in the study (22 male, 15 female), and were evenly distributed across our experimental conditions with respect to gender. The mean age of participants was 20.84 (*SD* = 4.15). Twenty-two participants had little or no experience playing 3D video games, and 15 reported that they were either experienced or very experienced. They were recruited from an undergraduate general psychology course, and were offered a research credit for participating. Participants were required to be between the ages of 18 and 65, have normal or corrected-to-normal vision, and be able to communicate comfortably in spoken and written English.

4.2 Study Design

Each participant was asked to explore the virtual environment described in Section 3. They were instructed to visit the offices in the virtual environment and turn on the computer screen in each room. Participants were randomly assigned to one of the following between-subjects conditions:

- **Distraction:** Each monitor displayed a picture of a unique object, presented in random order. Participants were instructed to remember the pictures, and were told that they would be tested afterwards.
- **Exploration:** Each monitor displayed the same generic login screen. They were instructed only to turn on the monitors, and were not given any memory test.

We hypothesized that the cognitive load imposed by the working memory task would distract participants, causing the scene changes to be less noticeable in the distraction condition than the exploration condition. Since participants’ familiarity with 3D video games may also influence the effectiveness of the redirection technique, we also investigated 3D video game experience as a between-subjects variable.

4.3 Equipment

Participants explored the virtual environment using a Virtual Research VR1280 head-mounted display. This display provides a stereoscopic view with a resolution of 1280 x 1024 per eye, a refresh rate of 60Hz, and a 60-degree diagonal field-of-view. The display also includes a barrier to block out real world visuals from the participants’ peripheral vision. For the interpupilary distance, we used the population average of 2.56 inches. Six degree-of-freedom head tracking was accomplished using the 3rdTech Hiball 3100 wide-area tracking system, which provided inside-looking-out optical tracking over an area of 14’ x 16’. The tracker was mounted to the band on the top of the head, and the offset between the tracker and display optics was corrected in software. Though the virtual environment did not include audio, participants wore the display's attached headphones to passively drown out ambient noise. To prevent tripping as participants circled the tracking area, all cables descended from a mounting frame on the ceiling in the center of the workspace and an experimenter followed each participant, holding the cables to prevent them from pulling. The virtual environment was implemented using the OpenSceneGraph renderer and VRPN for tracking system integration [26]. The experiment was run on a Dell Pentium 4 3.4GHz PC running Windows XP with 2 GB of RAM and an NVIDIA Quadro FX 4500 video card. Both eyes were rendered at 60 frames per second.

4.4 Methods

The study took approximately 45 minutes to complete. Participants first read an information sheet describing the study in detail. After being given an opportunity to ask questions, they then read and signed the informed consent form. After consent was obtained, participants then completed a demographic survey. As part of this questionnaire, they were asked to indicate their familiarity playing video games that took place in a 3D environment. We used this to categorize the participants into two groups: inexperienced (those who reported little or no experience with 3D video games) and experienced (those who reported that they were either experienced or very experienced). Afterwards, participants then completed the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [10].

After completing the pre-questionnaires, the experiment task was explained to participants, and they were fitted with the head-mounted display. It is important to note that we did not blindfold participants when entering the experiment area; therefore, they were able to observe the size of the physical space prior putting on the head-mounted display. Participants were given a short training session where they practiced walking around an example virtual environment for about two minutes. When the participants were ready to continue, the experiment tasks were then explained to them, and they were given an opportunity to ask questions. Then, the virtual office environment was loaded, and they explored the environment by visiting each of the 12 offices. It took approximately five minutes to completely explore the environment. After the participants walked out of the last office, the experimental session was concluded.

Immediately after the experimental session, the participants completed the SSQ post-test so that we could compare the change in reported symptoms from before to after the experimental session. Participants in the distraction condition were then asked to complete a memory recall test that required them to list all the pictures they could remember from the environment. This recall test was administered so that participants would not suspect deception on the latter questionnaires, but it was not included as one of our outcome measures.

Next, participants were asked to sketch a rough map of the environment on a sheet of blank paper. This was done to assess whether they were able to resolve the conflicting spatial layout information into a cohesive mental map. Since we are concerned with their understanding of the environment structure, we instructed them to draw the walls, rooms, and doorways, but not to include any objects or furniture. These maps were independently evaluated by three graders that were blind to the participants' condition, in a modified approach similar to Billinghurst et al. [2]. Graders were given the picture of the virtual office layout (see Figure 3.a) and told to subjectively rate how well the sketch represents the same environment as the picture on a scale from 1="not at all" to 5="very closely". The graders were told to ignore the drawing ability of the participant and judge the maps based on the structural similarity, not visual quality. After completing the sketch map, participants were asked to fill out the SUS Presence Questionnaire [29]. The presence ratings for the six questions were averaged together to yield a single SUS presence score ranging from 1 to 7, with higher scores corresponding to greater sense of presence.

Finally, the participants completed a questionnaire about their experiences in the virtual environment. The effectiveness of the change blindness redirection technique was primarily assessed through several real questions embedded in a list of decoy phenomena, similar to the approach used by Peck et al. [16]. Participants were asked, "Did you notice anything unnatural or odd about your virtual experience? Please rate the following statements. Please note that these phenomena may or may not have happened." They were then asked to rate each of the following statements on a scale of 0="did not notice or did not happen" to 6="very obvious" (the primary outcome measurements are italicized):

- I saw the virtual world get smaller or larger.
- *I felt like I was turning in circles.*
- I saw the virtual world flicker.
- I saw the virtual world get brighter or dimmer.
- *I saw that something in the virtual world had moved.*
- I saw the virtual world rotating.
- I felt like I was getting bigger or smaller.
- I felt like I was being moved around.
- I saw that something in the virtual world had changed size.

At the end of the virtual experience questionnaire, we also included free response questions to gather qualitative feedback. In particular, we included the following question to tease out whether participants were able to identify the scene change specifically: "In each room of the virtual environment, certain objects changed locations. If you can, please identify which objects changed and how they changed." To assess whether the redirection technique negatively impacted their experiences, we also asked participants to identify any aspects that took away from their experiences in the virtual world. At the conclusion of the experiment, participants were debriefed and given a final opportunity to ask questions or provide comments.

4.5 Results

Unless otherwise noted, all statistical results reported in this paper use a significance value of $\alpha = .05$. All analyses of variance (ANOVA) used Type III sum of squares to correct for the uneven proportion of 3D video game experience between groups.

4.5.1 Embedded Questions

Figure 4 shows the mean ratings for each of the embedded questions. Ratings for the decoy questions ranged from 0.70 to 2.30, indicating that some guessing occurred. The outcome question, "I saw that something in the virtual world had moved," was remarkably low (M = 1.00, SD = 1.87) and well within the same range as the decoy questions, indicating that the scene changes may have gone undetected by most participants. The other outcome question, "I felt like I was turning in circles," was a striking outlier (M = 4.00, SD = 1.68). This suggests that although participants may not have noticed the scene changes, they still had the general sense that they were walking in a loop within a limited space.

The ratings for the two embedded outcome questions were each treated with a 2x2 univariate ANOVA testing the effects of 3D video game experience and experimental task (distraction or exploration). For "I saw that something in the virtual world had moved," ratings were higher for experienced gamers (M = 1.73, SD = 2.28) than those inexperienced with 3D video games (M = 0.50, SD = 1.41), $F(1,33) = 4.44$, $p = .04$, $\eta_p^2 = .12$. The effect for experimental task was not significant, $p = .20$, nor was the interaction effect, $p = .10$. For "I felt like I was turning in circles," the analysis revealed non-significant effects for 3D video game experience, $p = .65$, experimental task, $p = .69$, and the interaction, $p = .07$.

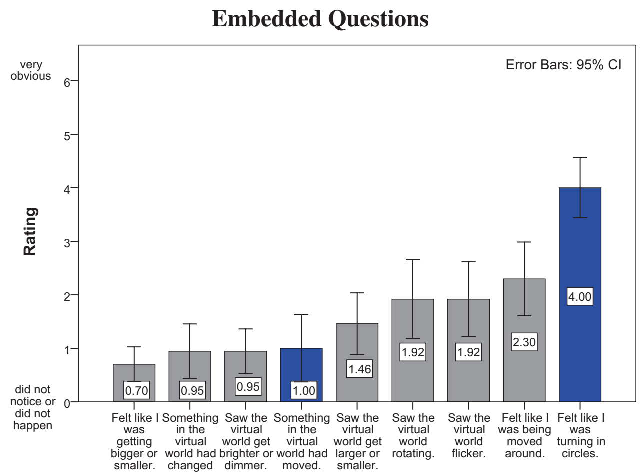
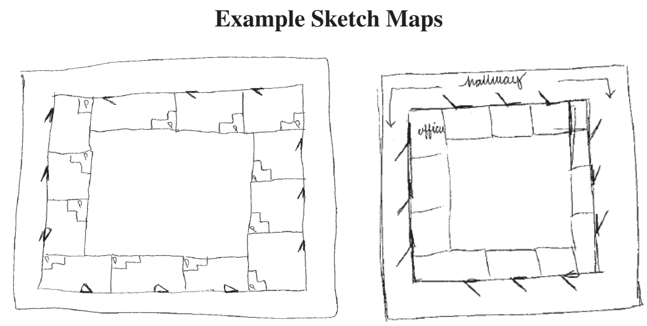


Figure 4: Results of the mean outcome ratings (shown in blue) embedded in a list of decoy questions. The rating that corresponds to noticing scene changes was remarkably low. While this indicates that scene changes went largely unnoticed, participants rated the feeling of turning in circles much higher than any of the other measures.



(a) Distraction Condition

(b) Exploration Condition

Figure 5: Two representative examples of the rough sketch maps that participants drew after exploring the environment. The sketch maps, as rated by three independent graders, were structurally similar to the static environment model in both of the experimental task conditions.

4.5.2 Sketch Maps

Overall, the sketch map grades were quite high (M = 4.22, SD = 0.79). On a grading scale of 1-5, only three out of 37 participants drew maps that received an average rating below three. Figure 5 shows representative examples of the sketch maps drawn by participants in each condition. These results indicate that even though the layout of the virtual environment was dynamically changing, participants' mental maps were structurally similar to the static layout we intended them to perceive. To test the effects of 3D video game experience and experimental task (distraction or exploration), the sketch map ratings were treated with a 2x2 univariate ANOVA. The analysis revealed non-significant effects for 3D video game experience, p = .70, experimental task p = .53, and the interaction, p = .30.

4.5.3 Other Measures

SUS presence average scores were treated with a 2x2 univariate ANOVA testing the effects of 3D video game experience and experimental task (distraction or exploration). Participants who were experienced with 3D games reported significantly higher presence scores (M = 5.16, SD = 0.93) than inexperienced participants (M = 4.18, SD = 1.10), $F(1,33) = 7.50$, $p = .01$, $\eta_p^2 = .19$. The main effect for experimental task was not significant, p = .66, nor was the interaction effect, p = .81.

Simulator sickness scores were treated with a 2x2 mixed ANOVA, testing the between-subjects factor of experimental task (distraction or exploration) and the within-subjects factor of time (before or after the VR session). The main effect for time was significant, $F(1,35) = 6.83$, $p = .01$, $\eta_p^2 = .16$, indicating participants reported higher simulator sickness from before (M = 11.73, SD = 12.35) to after the VR session (M = 21.33, SD = 21.88). The main effect for experimental task was not significant, p = .32, nor was the interaction effect, p = .75.

4.6 Discussion

The results from this initial user study were very promising. Ratings on the embedded questions indicated that the change blindness illusion is quite effective in virtual environments. Indeed, only one participant out of 37 (an experienced 3D gamer) noticed the door switch when asked to identify what changed on the qualitative questionnaire, stating, "When leaving the room I had noticed the door was on the opposite side, as if the door or the room had completely changed." All other participants either stated they did not notice any changes or guessed objects that never moved, such as the computer, objects on the desk, the trash bin, and the potted plant (similarly, answers on the embedded decoy questions were also indicative of guessing). Furthermore, ratings of similarity were high between the sketch maps and the static model we intended participants to perceive, indicating that although the environment model was dynamically changing, participants were still able to form a cohesive mental map. While participants rated that they felt to some degree that they were turning in circles, none of them mentioned this on the qualitative questionnaire when asked if anything took away from their virtual experience. We did, however, receive a number of positive comments that affirmed the effectiveness of the redirection technique; for example, one participant noted, "I truly felt like I was walking down hallways instead of circling the room."

While our manipulated variable - the addition of a working memory task for distraction - was not a statistically significant factor on any of our measures, we view this as a positive result, since the redirection technique proved startlingly effective. Results from the exploration condition indicate that the change blindness illusion is so convincing that no additional distractions are necessary. A secondary finding for this study is that participants with experience playing 3D video games reported higher sense of presence. We speculate that a familiarity with 3D gaming environments allows participants to more readily suspend disbelief when immersed in virtual reality, though the reasons for this difference remain unclear. Additionally, though there was an increase in reported simulator sickness, this may have been a consequence of our VR setup, and it is unclear from our data whether the redirection played any role.

5 Experiment 2: Follow-up Study

Given the highly promising results from Experiment 1, change blindness redirection seemed unbelievably effective. Thus, in Experiment 2, we attempted to perform an evaluation that would be more likely to "break" the technique. First, we investigated the effect of increasing the head-mounted display field-of-view (FOV). Recently developed displays such as the Fakespace Wide5 and the NVIS nVisor SX111 have made it possible to experience a much wider panorama than traditional 60-degree diagonal FOV displays. As several previous virtual environment studies have found that a wide FOV results in more accurate distance perception [11] and superior performance on walking and search tasks [1] [12] than a limited FOV, a wide FOV might allow participants to gather more spatial information about the virtual environment, which in turn might make them more likely to notice the structural manipulations used by our technique. Second, we included a pointing task before and after scene changes to determine whether the redirection technique interferes with participants' spatial orientation relative to the virtual world. Finally, we expanded our qualitative questionnaire with intentionally leading questions to see if we could get participants to identify the redirection technique.

5.1 Participants

A total of 40 people participated in the study (20 male, 20 female), and were evenly distributed across our experimental conditions with respect to gender. The mean age of participants was 35.38 (*SD* = 12.57). When participants were asked to identify their experience playing 3D video games, 32 had little or no experience, and 8 reported that they were experienced or very experienced. They were primarily recruited through craigslist online classifieds, and were offered a $20 gift card for participating. Participants were required to be over the age of 18, able to walk without assistance, have normal or corrected-to-normal vision, and able to communicate comfortably in spoken and written English. We excluded participants that were pregnant, had a history of epilepsy or seizures, or had an illness that could be transmitted by contact.

5.2 Study Design

Participants explored the virtual environment described in Section 3, and were given the same exploration task as Experiment 1. Pictures were displayed when participants approached the virtual computer monitors; however, they were instructed only that they needed to turn on the screens and were not told to remember the pictures. Participants were randomly assigned to one of the following between-subjects conditions:

- **Wide FOV:** The world was displayed using a 150-degree horizontal and 88-degree vertical FOV.
- **Narrow FOV:** The display was restricted to 48-degree horizontal and 36-degree vertical FOV by blacking out the peripheral pixels in software, simulating the limitations of commonly available head-mounted displays that use a 60-degree diagonal FOV.

We hypothesized that the scene changes would be more obvious to participants in the wide FOV condition. However, in light of the the highly positive results from Experiment 1, we were hopeful that the change blindness redirection technique would prove effective regardless of FOV.

5.3 Equipment

We used the same software as Experiment 1, but a different hardware setup. Participants explored the virtual environment using a Fakespace Wide5 head-mounted display, which provides a wider field-of-view than most commonly available displays (total FOV of 150 degrees horizontal and 88 degrees vertical). The display uses a variable resolution with higher pixel density in the central region and lower resolution in the periphery. We used the population average interpupilary distance of 2.56 inches. Additionally, headphones were worn to issue audio instructions to the participants as well as to passively drown out ambient noise. It should be noted that although we used a wide FOV display, we did not place a barrier around the edges of the display to block out real world visuals from participants' peripheral vision.

Tracking was accomplished using a Phasespace Impulse Motion Capture System, which provided outside-looking-in optical tracking using an array of 46 high-resolution cameras arranged in a circular pattern with a 20' approximate radius. Five LED markers were mounted on the head-mounted display, forming a rigid body that was tracked with six degrees-of-freedom at 480 Hz. Two experimenters were present during the VR sessions to manage the cables in order to prevent participants from tripping. The experiment was run on a dual Intel Core i7 2.93 GHz PC with a total of eight cores running Windows Vista with 6 GB of RAM and an NVIDIA 9800 GT graphics card. Each eye was rendered at 60 frames per second.

5.4 Methods

The experimental procedure was the same as Experiment 1 (see Section 4.4); however, we expanded our measures to gather additional information. First, we added a pointing test to the virtual reality session. Periodically, participants were given pre-recorded audio instructions through their headphones that told them to stop and point back to their starting location in the virtual world by turning until an on-screen arrow was pointed in the correct direction, and then pressing a button on a handheld Nintendo Wii remote. This test was performed to gather information on how well participants could reorient themselves after the scene change occurred. There were a total of four pointing trials, once per middle room in each hallway. Half of the pointing trials were completed before the scene change as the participant approached the computer screen, and half were completed after the scene change when the participant turned around and approached the altered door. The order of presentation was balanced across the conditions. We recorded the angular error in degrees for each pointing trial.

After participants completed the sketch map test, we also asked them to sketch out a rough map of a single office on a separate sheet of paper. Our primary outcome measurement for this test was to record where participants remembered the door: in the corner prior to the scene change, in the corner after the scene change, or in the middle of the wall. These results were intended to characterize how participants interpreted the conflicting spatial information introduced by the scene change. This information could explain whether participants relied on their first impressions, overwrote their initial mental model, or combined the conflicting features in some way.

Finally, we also made several modifications to the virtual experience questionnaire. To reduce ambiguity in the list of embedded questions, we changed the statement, "I felt like I was turning in circles," to "I felt like I was being turned around." In the qualitative section, we asked the following leading questions to more thoroughly draw out what participants noticed and felt during their experience: (1) "At any point during your experience, did you feel turned around? If so, please describe how you felt and when you felt it." (2) 'You explored a very large virtual environment. However, the walking area you were actually in was much smaller. How do you think that happened?" (3) "When you were inside each room, certain objects or structures in the room changed location while your back was turned. If you can, please identify what changed and how it changed." (4) "If you noticed that something changed, how did this impact your experience of the virtual world?"

5.5 Results

Due to the fact that so few of our participants were experienced gamers (8 out of 40), we did not have enough data to include 3D video game experience in the analyses for this experiment.

5.5.1 Pointing Test

Figure 6 shows the mean pointing test errors in degrees for each of the FOV conditions. These results were treated with a 2x2 mixed ANOVA, testing the between-subjects factor of FOV (wide or narrow) and the within-subjects factor of presentation (before or after the scene change in each room). Participants using the wide FOV were able to more accurately point back to their starting location in the virtual world than those using a narrow FOV, $F(1,38) = 4.43$, $p = .04$, $\eta_p^2 = .10$. The main effect for method of presentation was not significant, $p = .51$, nor was the interaction effect, $p = .87$.

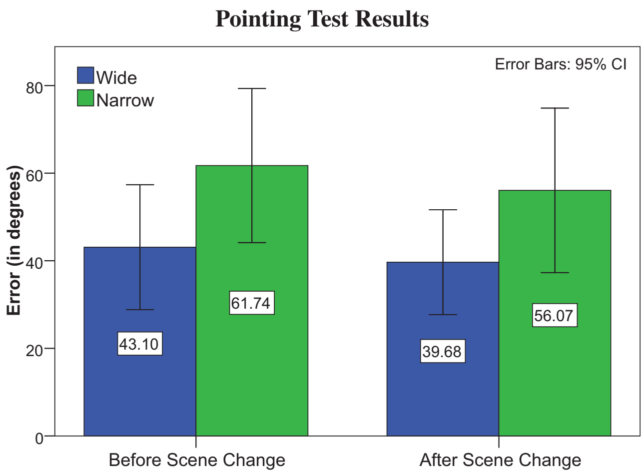


Figure 6: Mean errors from the pointing test (in degrees) in the wide and narrow field-of-view conditions. Participants using the wide field-of-view were able to more accurately point back to their starting location in the virtual world than those using the narrow field-of-view, regardless of whether the test occurred before or after the scene change in each room.

5.5.2 Embedded Questions

The mean ratings for each of the embedded questions were similar to Experiment 1. Ratings for the decoy questions ranged from 0.52 to 1.50. The outcome question pertaining specifically to change blindness, "I saw that something in the virtual world had moved," was again low overall ($M = 0.67$, $SD = 1.59$). The revised outcome question, "I felt like I was being turned around," was still the highest rating ($M = 2.48$, $SD = 2.46$). Independent samples t-tests evaluating the effect of FOV were not significant for either the former outcome question, $p = .92$, or the latter, $p = .34$.

5.5.3 Sketch Maps

We excluded one participant's sketch map from this analysis who did not understand the instructions. On average, sketch map scores were graded as structurally similar to the static environment layout we had intended ($M = 3.67$, $SD = 1.00$). Though the grades were not as high as Experiment 1, this again indicates that participants were internalizing a mental map despite the fact that the layout of the environment was dynamically changing. An independent samples t-test for the effect of FOV was not significant, $p = .29$. Analysis of the separate single office maps revealed that 22 maps depicted the door in its original corner (the door's location before the scene change), one placed it in the other corner (the door's location after the scene change), 14 placed it in the middle of the wall (blending the two locations), and three were missing the door or were inconclusive. A χ^2 test for the effect of FOV was not significant, $p = .37$.

5.5.4 Other Measures

SUS presence average scores were moderately high overall ($M = 5.40$, $SD = 1.07$), and an independent samples t-test for the effect of FOV results was not significant, $p = .36$. Simulator sickness scores were treated with a 2x2 mixed ANOVA, testing the between-subjects factor of FOV and the within-subjects factor of time (before or after the VR session). Simulator sickness did not significantly increase from before ($M = 8.88$, $SD = 12.95$) to after immersion ($M = 9.72$, $SD = 15.36$), $p = .63$. The main effect for FOV was not significant, $p = .98$, nor was the interaction effect, $p = .96$.

5.6 Discussion

Overall, our results from this study are consistent with the findings from the first experiment. We observed fewer incidences of guessing on the questionnaires, although this may be due to differences in our population samples, since the participants in the first experiment were university students, while the second study drew from a more general population. When asked to identify what changed on the qualitative questionnaire, none of the participants indicated that they noticed the scene change during their VR session. However, one participant was able to figure it out after reading the leading questions and reflecting on the experience, writing, "Now that I think about it, I have a feeling that the door seemed to have changed places and wasn't where I expected it to be (this might have happened while I was looking at the computer screen), but before reading this question I thought that was just due to it being the virtual environment and me not being accustomed to it, so I am not really sure." In a follow-up question to determine how this impacted the experience, this participant further explained, "It didn't impact much. While in the virtual world, I thought everything was normal." This interesting anecdote suggests that perceptual illusions may be have broad applications in a virtual world, since some people may attribute their uncertainty to being in an unfamiliar, simulated environment. Similar to the first experiment, we received many positive comments that pointed to the effectiveness of the redirection technique, such as, "My mind was convinced by the walking space in front of me. I believed the long hallways I saw," and "I may have indeed been turned around, but I did not feel so." Some participants, however, wrote comments such as, "As I left each room and turned in the hallway, I thought I was going in circles," though it should be noted that some of our free response questions were intentionally leading to draw out these kind of impressions. Interestingly, when asked to speculate on how they were able to walk in a virtual environment that was larger than the physical space, many participants indicated they did not know, and scaled translational gain techniques were a common suggestion among those who chose to speculate.

The single office maps suggest that most participants stuck with their first impressions of the environment, which is one of the suggested hypotheses to explain change blindness [21]. Those that drew the door in the middle of the wall could either be explained by a failure to store the door's specific location in their mental maps or by combination of the conflicting spatial features. Our results, however, do not support the hypothesis that the original scene information would be overwritten. It was interesting that applying the scene change immediately before the pointing test did not reduce participants' pointing accuracies. Though the difference in errors before and after redirection was not significant, participants on average were actually slightly more accurate at pointing towards the start location after the scene change, even though the relative position of this point in the virtual world had been drastically moved. Thus, our results suggest that participants were using the door and hallway as spatial cues to orient themselves relative to the surrounding environment despite the fact that these features were being manipulated. A secondary finding of this study is that participants were significantly more accurate when using a wide FOV as opposed to the limited FOV used by traditional head-mounted displays. This is consistent with several previous studies of FOV in virtual environments [1] [11] [12]. Finally, our simulator sickness results suggest that the increase in reported symptoms during Experiment 1 may have been due to the specific VR setup that was used and not the change blindness redirection technique.

6 Conclusions and Future Work

In this paper, we described change blindness redirection, a novel redirection technique for enabling real walking through large virtual environments in a limited physical space without introducing sensiromotor conflicts. Though the scenario tested in our experiments was highly constrained, our studies were intended to explore the effectiveness of the change blindness illusion, not to present a generalizable redirection algorithm. The results from these studies were highly promising, as only one out of 77 participants was able to definitively notice that a scene change had occurred while exploring the virtual environment. Thus, we conclude that change blindness redirection provides a remarkably compelling illusion, though it is limited to environments where the architecture can be manipulated. However, generalizing change blindness redirection for use in different types of environments is an important direction for future work. While change blindness techniques work well in constrained interior environments, other redirection techniques also have their own set of advantages and disadvantages depending on the environment and situation. With a variety of redirection techniques at our disposal, we suggest that a generally applicable redirected walking solution may be achievable by applying multiple techniques in a single environment walkthrough.

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