Effects of Redirection on Spatial Orientation in Real and Virtual Environments

Evan A. Suma* David M. Krum* Samantha Finkelstein† Mark Bolas*‡

*USC Institute for Creative Technologies †UNC Charlotte ‡USC School of Cinematic Arts

ABSTRACT

We report a user study that investigated the effect of redirection in an immersive virtual environment on spatial orientation relative to both real world and virtual stimuli. Participants performed a series of spatial pointing tasks with real and virtual targets, during which they experienced three within-subjects conditions: rotation-based redirection, change blindness redirection, and no redirection. Our results indicate that when using the rotation technique, participants spatially updated both their virtual and real world orientations during redirection, resulting in pointing accuracy to the targets' recomputed positions that was strikingly similar to the control condition. While our data also suggest that a similar spatial updating may have occurred when using a change blindness technique, the realignment of targets appeared to be more complicated than a simple rotation, and was thus difficult to measure quantitatively.

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, spatial orientation

1 INTRODUCTION

Physical space limitations are a troublesome impediment to natural locomotion in immersive virtual environments. Real walking provides many advantages over less natural travel techniques, including a greater sense of presence [15], improved performance on travel and search tasks [9] [13], and benefits for memory and attention [12]. However, a real walking interface ultimately restricts the exploration of the virtual environment to the dimensions of the physical workspace and motion tracking area. To relax these limitations, a number of redirection techniques have been proposed to decouple the user's locations in the physical and virtual worlds, allowing walking through virtual environments that may be considerably larger than the real world space. Suggested redirection techniques have ranged from manipulating perceptual self-motion cues, such as applying rotational gains [6] or scale factors to forward movements [4], to more complicated approaches involving structural manipulation and change blindness [11].

Redirection techniques attempt to imperceptibly physically reorient the user without disrupting their spatial awareness in the virtual world. Previous research suggests that when users are redirected in a virtual environment, their orientation relative to the virtual world is updated, as measured by pointing and map tests [5]. However, little research has been done to investigate how redirecting users in a virtual environment impacts their spatial orientation in the real world. Does the user's perceived orientation relative to the real world also get updated, or do they maintain a distinct model for real world orientation that is unaffected by manipulations in the virtual environment? This is an important question for applications involving physical reflex actions, such as immersive training. For example, a soldier may need to quickly react to threats in a simulator by moving around or finding protective cover in an environment. If the user was redirected in the virtual world, but instinctively reacted to a residual real world model, then redirection may not be appropriate for these purposes, and at worst may provide negative training. Thus, in this paper, we describe an experiment that was performed to probe the relationship between the real world and virtual world models for spatial orientation using a pointing task during which participants were redirected.

2 BACKGROUND AND RELATED WORK

Spatial updating is the process by which people keep track of the spatial relationship between themselves and the surrounding environment. During navigation, humans combine visual information from their surroundings with body-based information from the translational and rotational components of movement, also known as path integration. The user's awareness of their own body movements, involving proprioceptive and kinesthetic cues, is a critical aspect of navigational search, and greatly improves spatial updating compared to situations where only visual feedback is provided [2] [8]. These body-based cues allow better spatially orientation [1] and knowledge transfer from VR to the real world [3].

Despite the importance of proprioceptive and kinesthetic cues for spatial updating, recent studies in virtual environments have also shown that purely visual stimuli are sufficient for automatic spatial updating regardless of any vestibular or kinesthetic information [7]. Additionally, research in redirected walking has found that visual information tends to dominate over vestibular cues when the magnitude of the conflict is beneath a certain detection threshold [6] [10]. However, previous research has focused primarily on the users' spatial orientations within the virtual world. Until virtual reality technology progresses such that a virtual environment is perfectly indistinguishable from the real world, on some level users experience presence in both the real and virtual environments simultaneously, and this dual presence may influence their behavior. If the user is maintaining two distinct world models, it is not clear that visual and kinesthetic cues are uniformly important for spatial updating in both models, nor is it necessarily obvious that manipulating spatial orientation in the virtual context will affect the real one.

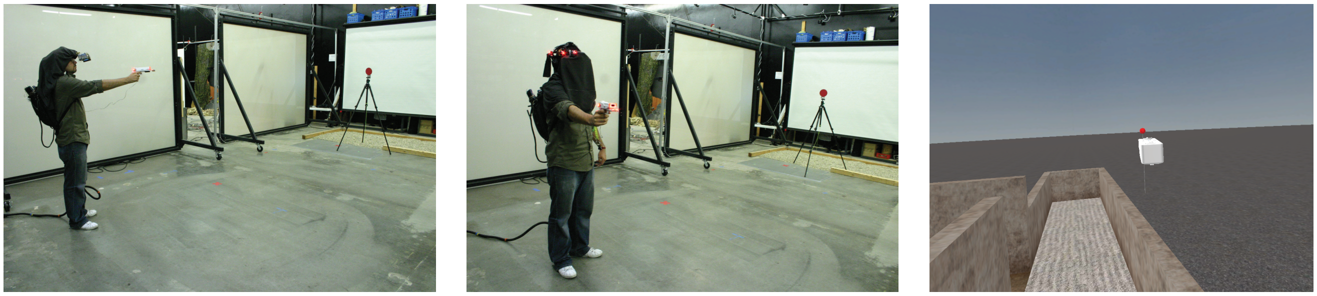
3 METHODS

A total of 18 people participated in the study. However, the motion capture data for 2 participants were incomplete due to equipment failures, resulting in a final sample of 16 people (12 male, 4 female). The mean age of participants was 28.50 (*SD* = 8.49). The distribution of self-identified video game experience consisted of 8 non-gamers, 3 casual gamers, and 5 hard-core gamers. They were primarily recruited through email and craigslist online classifieds, and were offered a $20 gift card for participating. We performed a within-subjects study with three redirection conditions (rotation

---

*e-mail: {suma, krum, bolas}@ict.usc.edu
†e-mail: sfinkel1@uncc.edu

IEEE Symposium on 3D User Interfaces 2011
19-20 March, Singapore
978-1-4577-0037-8/11/$26.00 ©2011 IEEE



(a) Initial pointing to a real world target (b) Initial pointing to a virtual world target (c) Pointing in the virtual environment

Figure 1: (a) At the beginning of each trial, the head-mounted display visor was lifted and participants pointed to a real world target. (b) After lowering the visor and hood, the participants pointed to a separate target in the virtual environment. (c) The target was initially visible in the virtual world. After participants pointed to it, the target faded away and they had to remember its location.

technique, change blindness technique, and control) presented four times each in random order, for a total of 12 trials. For each trial, participants were asked to walk through a virtual environment using a head-mounted display and keep track of the locations of a real world and a virtual world target. To begin each trial, participants would walk to a predefined location in an empty virtual world, marked by an 'X' on the ground. The experimenter would then help them lift up head-mounted display visor so that they could look around and point at a real world target, which was a six-inch diameter red circle that had been randomly placed on a tripod at approximate eye level in one of the four corners of the room (see Figure 1.a). The visor was then lowered in front of their eyes, displaying a minimalistic virtual world with a walking path and single room. Participants were instructed to point at a virtual world target that was placed in a different location, which was randomly selected from the remaining corners of the tracking space (see Figure 1.b). These initial pointing tasks were performed to verify that participants viewed each target and performed the task correctly, but were not analyzed as part of our results. After pointing, the virtual target disappeared, and they were asked to walk down a virtual path to the next marker, which was located in the corner of the virtual room. When they reached the marker, a visual distractor (hummingbird) would appear for several seconds and fly back and forth, and participants were instructed to turn their head and watch until it disappeared. During the distraction phase, one of the following three redirection techniques were applied:

- **Rotation:** The virtual environment was slowly rotated about the user as a function of head turn speed, as suggested by Peck et al. [5].
- **Change Blindness:** The door to exit the virtual room and the adjoining hallway was instantaneously rotated by 90 degrees behind the user's back, as described by Suma et al. [11].
- **Control:** No redirection was applied.

While the visual distractor was only necessary to ensure that the rotation technique was imperceptible, we included it in all conditions to be consistent and avoid a potential confound. For the rotation condition, we applied rotational gains of 10% with head turn and 5% against head turn. Due to study time constraints, these gains are higher those used by Peck et al., who selected gains of 3% with head turn and 1% against head turn [5]. However, we compensated for this by making the distractor move fairly rapidly back and forth about a circumference 3 feet away from the user at a rate of 55 degrees per second. When the virtual environment had rotated a total of 90 degrees about the user, the distractor disappeared. To ensure that the amount of distraction time was consistent, we still kept track of head rotation in the other two conditions and used the same algorithm to calculate when the distractor should disappear, even though no rotation was applied. After the distraction phase, participants walked to the next marker, which required them to exit the virtual room and proceed further down the walking path. Upon reaching the marker, they were then instructed to point back to where they remembered the virtual target, followed by the same task for the real world target. The specific order of the pointing tasks (real-virtual-virtual-real) was selected to minimize the number of times the participant would have to switch contexts back and forth between the real and virtual worlds. After completing each trial, the real world target was moved to a different corner of the tracking space, and this process repeated until all 12 trials were completed.

We hypothesized that when the redirection techniques were applied, participants would *point to the virtual world target as if its position had been rotated along with the rest of the virtual environment*. Furthermore, we also hypothesized that the visual feedback from the virtual world would dominate over the kinesthetic cues, which would result in them *pointing to real world targets at positions that were also rotated along with the virtual environment.*

3.1 Equipment

Participants explored the virtual environment using a Fakespace Wide5 head-mounted display, which provides a total FOV of 150 degrees horizontal and 88 degrees vertical. This display uses a variable resolution with higher pixel density in the central region and lower resolution in the periphery. The interpupilary distance was set to the population average of 2.56 inches. To hold the display control box and other necessary hardware, participants wore a backpack that was tethered to a single run of cable. Two experimenters were present at all times during the study to manage the cables, allowing the participant to walk around freely throughout the entire space. For tracking the participants' movements, we used a PhaseSpace Impulse Motion Capture System, which provided outside-looking-in optical tracking using an array of 52 high-resolution cameras arranged in a pattern covering a 36' x 36' area. Seven LED markers were mounted on the display in a ring around the user's head, ensuring visibility from all angles. Pointing was accomplished using a Nintendo Wiimote mounted on a Nyko PerfectShot pistol grip with four mounted LEDs for tracking with the PhaseSpace system. Participants were able to point at a target by aiming the "gun," followed by pressing the trigger on the pistol grip. A virtual replica of the Wiimote was rendered in the virtual environment to provide visual feedback when pointing.

Since any sensory cues from the real world could potentially confound the study, we were careful to design our VR setup to be as immersive as possible. To eliminate peripheral visual cues from the real world, we mounted an opaque, lightweight Lycra fabric from the ring above the display optics, but just below the tracked LEDs. This formed a hood that fell in front of the display optics, draped over the shoulders, and rested against the chest. To drown out ambient and transient noise in the real world, participants wore Pioneer SE-DJ5000 sound-isolating headphones, looping brown noise (approx. 6 dB rolloff per octave, 44kHz sampling rate) at comfortable levels observed to effectively obstruct conversation, noise from cable drag, and other ambient sounds present in our lab. Instructions for each stage in the task were delivered via a text-to-speech voice in the headphones. The experiment was run on a dual Intel Core i7 2.93 GHz PC running Windows Vista with a total of eight cores. The PC had 6GB of RAM and an NVIDIA 9800 GT graphics card. Each eye was rendered in software at 60 frames per second. The virtual environment was implemented using the OpenSceneGraph renderer and VRPN [14] to facilitate communication with the tracking system.

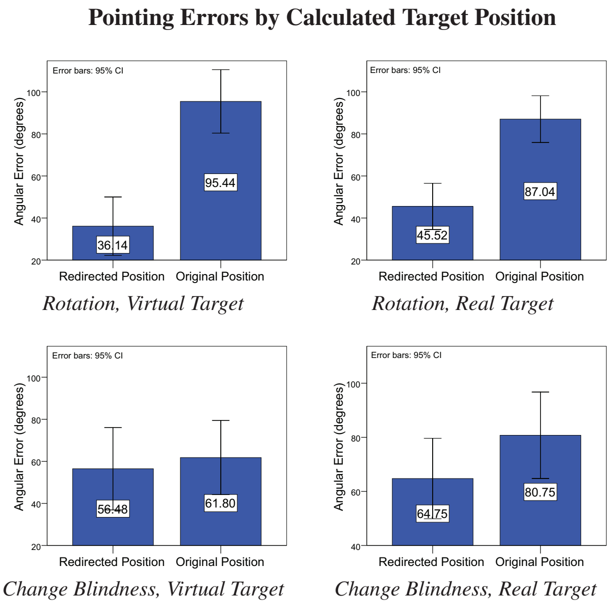
3.2 Measures and Procedures

The study took approximately one hour to complete. First, participants read the informed consent form that described the study in detail, and the experimenter verified that the participant met the inclusion criteria and answered questions about the study. After consent was obtained, participants were fitted with the head-mounted display and the experiment tasks were explained. To provide training, participants performed a full practice trial in which the experimenter clarified the computer instructions at each step. They were not informed that they would be redirected during the tests. After completing the training, participants performed six trials, during which the experimenter remained silent unless assistance was required. In order to reduce the risk of simulator sickness, the VR gear was removed and participants were asked to take a 3-5 minute break after completing the sixth trial. When they were ready to resume, the VR gear was donned and the remaining six trials were completed.

For two pointing tasks at the end of each trial, we recorded the angular error in the XY plane (ignoring height) between the participants' pointing vector and the vector to the target location. For the rotation and change blindness conditions, we also calculated these pointing errors for each target's redirected location relative to the virtual world. In the rotation condition, the target's redirected location was calculated by matching the virtual environment rotation about the user's head position. In the change blindness condition, we calculated the location by rotating the target about the center of the virtual world by 90 degrees. However, it should be noted that since this technique relies upon complex structural alterations to portions of the environment, a global rotation may only be an approximation of the user's mental realignment. For each of the three redirection conditions, the final pointing errors from the respective four trials were averaged to provide the following mean angular pointing errors for each target location: (1) virtual target's original position, (2) virtual target's redirected position[1], (3) real target's original position, and (4) real target's redirected position[1]. After finishing the VR session, participants completed a questionnaire that included qualitative, demographic, and video game experience questions.

4 RESULTS

Preliminary analysis revealed that one participant had extremely high pointing errors of over 100 degrees (greater than 3 standard deviations from the mean) for the initial virtual target pointing tasks in each trial. Since these pointing tasks occurred while the target was still visible in the virtual world, this indicates that the participant did not understand the task, and was therefore excluded from our analyses. Unless otherwise noted, all statistical results reported in this paper use a significance value of $\alpha = .05$.



Rotation, Virtual Target *Rotation, Real Target*

Change Blindness, Virtual Target *Change Blindness, Real Target*

Figure 2: In the rotation condition, pointing errors were considerably lower when calculated based on the target's redirected position, regardless of whether the target was virtual or real. A similarly strong effect was not observed in the change blindness condition.

We compared the average angular pointing errors using a 3x2 repeated-measures ANOVA, testing the within-subjects effects of redirection technique (control, rotation, or change blindness) and target environment (real or virtual). For the rotation and change blindness conditions, we used the pointing errors calculated from the target's redirected position. The analysis revealed significant a main effect for redirection technique, $F(2,28) = 6.56$, $p < .01$, $\eta_p^2 = .32$. Pairwise comparisons using Bonferroni adjusted alpha values indicated that the change blindness pointing errors ($M = 60.62$, $SE = 7.25$) were significantly higher than the errors in the control condition ($M = 40.23$, $SE = 4.79$), $p = .04$, and the rotation condition ($M = 40.83$, $SE = 4.82$), $p = .05$. However, the rotation and control conditions were not significantly different, $p > .99$. Additionally, there was also a significant main effect for target environment, $F(1,14) = 5.73$, $p = .03$, $\eta_p^2 = .29$, with lower pointing errors for the virtual world targets ($M = 42.33$, $SE = 5.37$) than the real world targets ($M = 52.12$, $SE = 4.24$). The interaction was not significant, $p = .95$.

To evaluate the differences between the pointing errors calculated from the targets' original and redirected positions, the pointing errors from the two redirection conditions were treated with a 2x2x2 repeated-measures ANOVA, testing the within-subjects effects of target environment (real or virtual), target position (original or redirected), and redirection technique (rotation or change blindness). The analysis revealed a significant interaction effect between redirection technique and target position, $F(1,14) = 10.86$, $p < .01$, $\eta_p^2 = .44$, as well as a significant main effect for target position, $F(1,14) = 25.06$, $p < .01$, $\eta_p^2 = .64$. None the other main effects or interactions were significant. To probe the interaction effect, we conducted post-hoc paired-sample t-tests using a Bonferroni-adjusted alpha threshold of $\alpha = 0.0125$ for multiple comparisons. In the rotation condition, the differences between redirected and original position pointing errors were significant for both virtual targets, $p < .01$, and real world targets, $p < .01$. However, in the change blindness condition, these differences were not as strong for either virtual targets, $p = .71$, or real world targets, $p = .16$. The mean pointing errors arranged according to redirection technique

---

[1] Redirected positions were not present in control condition.

and calculated target position are shown in Figure 2.

5 DISCUSSION

The redirected position errors for the rotation technique were extremely similar to the pointing results from the control condition. It is very clear from our data that after being redirected by the rotation technique, participants did not point back to the target's original position, but rather to an updated position that reflected the virtual world rotation. The effect was strong for both virtual and real world targets, which supports our hypothesis that manipulating the participants' spatial orientations in the virtual environment would also carry over to their real world orientation. While there was a similar trend when the change blindness technique was used, the effect was not as pronounced. We believe this may be explained by the structural manipulations that change blindness techniques rely upon, since this alters the relationship between salient features of the environment that were being used to judge the relative position of the target. A global rotation of the targets about the center of the world was most likely just an approximation of the more complicated mental realignment that occurred. It should be noted that errors based on the targets' original locations before redirection were high, which suggests that the change blindness technique did realign the targets relative to the virtual world, even though the model for computing the target locations after redirection is unclear.

Our initial assumption in designing this experiment was that people would maintain simultaneous models of the real world and the virtual environment. However, based on participant feedback and our observations during the experiment, we began to question this premise. Hanging on the real world model when fully immersed seems to be very difficult, and requires active concentration. As one participant noted, "I would simply forget where I was in the real world until it was time to interact with the real world again." We observed several participants employing very interesting strategies to help them keep track of the targets after they were no longer visible. These participants would initially turn back and forth between the targets and gesture, using their bodies to measure the relative angles. These gestures were often repeated during the final pointing tasks, suggesting that these participants were leveraging body motion and proprioceptive cues as mnemonic devices to store spatial information. We cannot analyze this behavior since we did not perform full body motion capture during this experiment; however, this would be an important question for future studies of spatial orientation in virtual environments.

We received generally positive comments about the real world sensory deprivation methods we employed (the hood and headphone noise), and participants indicated that they could not see or hear anything from the real world while they were immersed. Interestingly, many participants made negative comments about the hummingbird, and verbally indicated to us afterwards that the distractor was tedious. In fact, many participants requested to shoot the bird, most likely because of the pistol-shaped pointing device. Based on these comments, we suggest that a purely visual distractor might not be the best approach for repeated use. For redirection techniques that rely on distractors, including them in some sort of interactive task, such as a shooting game, may be preferred by users.

6 CONCLUSION

In this paper, we described a study that investigated spatial orientation in the real and virtual world, as measured by a pointing task, while visual cues from the virtual environment were manipulated. Our results indicate that when using the rotation technique, participants spatially updated both their virtual and real world orientations during redirection, resulting in pointing accuracy to the targets' recomputed positions that was strikingly similar to the control condition. While our data also suggest that a similar spatial updating may have occurred when using a change blindness technique, the realignment of targets appeared to be more complicated than a simple rotation, and was thus difficult to measure quantitatively. In the future, we plan to investigate the effect of allowing visual and audio cues from the real world to "seep" in to the virtual environment, to see if they dampen this effect. We also plan to investigate whether these real world spatial cues can be simulated and manipulated in order to augment redirection within the virtual environment.

7 ACKNOWLEDGMENTS

The authors would like to thank the ICT staff and students that assisted with the experiment, including David Nelson, Thai Phan, Logan Olson, Kedar Reddy, Diane Tucker, and Tom Guyette.

REFERENCES

[1] N. H. Bakker, P. J. Werkhoven, and P. O. Passenier. The effects of proprioceptive and visual feedback on geographical orientation in virtual environments. *Presence: Teleoperators and Virtual Environments*, 8(1):36–53, 1999.

[2] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis. Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence: Teleoperators & Virtual Environments*, 7(2):168–178, 1998.

[3] M. J. Farrell, P. Arnold, S. Pettifer, J. Adams, T. Graham, and M. MacManamon. Transfer of route learning from virtual to real environments. *Journal of Experimental Psychology: Applied*, 9(4):219– 227, 2003.

[4] V. Interrante, B. Ries, and L. Anderson. Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *IEEE Symposium on 3D User Interfaces*, pages 167–170, 2007.

[5] T. C. Peck, H. Fuchs, and M. C. Whitton. Improved redirection with distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments. In *IEEE Virtual Reality*, pages 35–38, 2010.

[6] S. Razzaque. *Redirected Walking*. PhD thesis, University of North Carolina at Chapel Hill, 2005.

[7] B. Riecke, D. Cunningham, and H. Bülthoff. Spatial updating in virtual reality: the sufficiency of visual information. *Psychological Research*, 71(3):298–313, 2007.

[8] R. A. Ruddle and S. Lessels. For efficient navigational search, humans require full physical movement, but not a rich visual scene. *Psychological Science*, 17(6):460–465, 2006.

[9] R. A. Ruddle and S. Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction*, 16(1):1–18, 2009.

[10] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):17–27, 2010.

[11] E. Suma, S. Clark, S. Finkelstein, and Z. Wartell. Exploiting change blindness to expand walkable space in a virtual environment. In *IEEE Virtual Reality*, pages 305–306, 2010.

[12] E. Suma, S. Finkelstein, S. Clark, P. Goolkasian, and L. Hodges. Effects of travel technique and gender on a divided attention task in a virtual environment. In *IEEE Symposium on 3D User Interfaces*, pages 27–34, 2010.

[13] E. Suma, S. Finkelstein, M. Reid, S. Babu, A. Ulinski, and L. Hodges. Evaluation of the cognitive effects of travel technique in complex real and virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 16:690–702, 2010.

[14] R. M. Taylor, T. C. Hudson, A. Seeger, H. Weber, J. Juliano, and A. T. Helser. VRPN: a device-independent, network-transparent VR peripheral system. In *ACM Virtual Reality Software & Technology*, pages 55–61, 2001.

[15] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks. Walking > walking-in-place > flying, in virtual environments. In *ACM SIGGRAPH*, pages 359–364, 1999.