Evaluation of Reorientation Techniques and Distractors for Walking in Large Virtual Environments

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Abstract—Virtual Environments (VEs) that use a real-walking locomotion interface have typically been restricted in size to the area of the tracked laboratory space. Techniques proposed to lift this size constraint, enabling real walking in VEs that are larger than the tracked laboratory space, all require reorientation techniques (ROTs) in the worst-case situation—when a user is close to walking out of the tracked space. We propose a new ROT using visual and audial distractors—objects in the VE that the user focuses on while the VE rotates—and compare our method to current ROTs through three user studies. ROTs using distractors were preferred and ranked more natural by users. Users were also less aware of the rotating VE when ROTs with distractors were used. Our findings also suggest that improving visual realism and adding sound increased a user's feeling of presence.

Index Terms—Virtual environments, walking, locomotion, user studies, reorientation techniques.

1 Introduction

Real walking in Virtual Environments (VEs) is more natural and produces a higher sense of presence than other locomotion techniques, such as walking-in-place and joystick interfaces [1], [2]. Omnidirectional treadmills do not enable real walking since users must "readapt" to real motion after extensive training [3]. However, VEs using a real-walking locomotion interface have typically been restricted in size to the area of the tracked laboratory space. Techniques have been proposed to lift this size constraint, enabling real walking in VEs that are larger than the tracked space [4], [5], [6], [7], [8], [9], [10]. Each of these large-area walking VE methods relies on a reorientation technique (ROT) to handle the case when the technique fails and the user is close to walking out of the tracked space. When such an event happens, ROTs must stop the user and rotate the VE around her current virtual location, placing the immediately expected user path back within the tracked space. The user must also reorient herself by turning around in the real environment so she can follow her desired path in the newly rotated VE.

ROTs are required to enable free exploration of large VEs without the use of joysticks, walking-in-place interfaces, treadmills, or bicycles [11], [12], [3], [13], [14]. We want to provide users with the most physically accurate VE experience possible. We hypothesize that current ROT implementations cause breaks in presence, which detract from the immersive VE experience. In this paper, we introduce a new ROT and compare our method to existing ROTs through three user studies. We evaluate each ROT based on *presence*, user-ranked *preference*, and user-ranked *naturalness*.

Our method introduces the concept of a distractor—an object, sound, or combination of object and sound in the VE that the user focuses on while the VE rotates, reducing perception of the rotation and, thus, reducing the likelihood of a break in presence. In the three studies, we compare our new distractor technique to previously reported techniques. The first two studies were presented in [15]. The methods introduced by Razzaque et al. [5], [6], [7] and Williams et al. [9], [10] induce the user reorientation via audio instructions, rotating the VE while the user is following the instructions. Nitzsche et al. and Su rotate the VE without warning or additional instructions [4], [8].

2 Background

Three real-walking techniques exist for exploring large immersive VEs and each method suggests its own ROT to enable free exploration. Redirected walking [5], [6], [7] is a technique that exploits the imprecision of human perception of self-motion—the motion of humans based on sensory cues—and modifies the direction of the user's gaze by imperceptibly rotating the VE around the user. The primary design goal of this technique is that it be imperceptible to the user. Razzaque suggests an ROT with a loudspeaker in the VE that asks the user to stop, turn her head back and forth, and continue walking in the same direction. Razzaque determined that a user is least likely to notice extra rotation while she is turning her head because of the imprecision of human self-motion perception. Redirected walking rotates the VE during such moments, moving the user's path so that it falls within the tracked environment.

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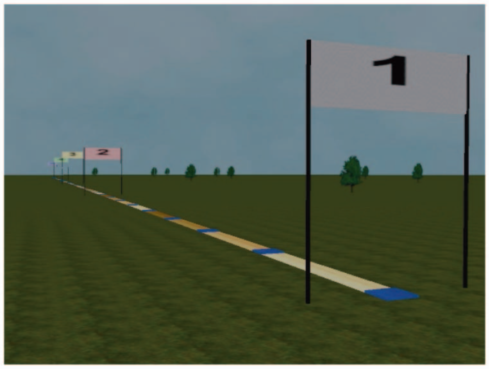

Fig. 1. VE used in Experiments 2 and 3.

Fig. 2. Laboratory layout used in Experiments 2 and 3.

Motion compression [4], [8] rotates the VE such that the predicted user path is the largest possible arc that can fit into the tracked laboratory space and, like redirected walking, continuously updates the location and the rotation of the VE relative to the laboratory space. Unlike redirected walking, motion compression does not make imperceptibility of rotation a primary goal. The ROT used in motion compression is built into the motion compression algorithm: as the user approaches the edge of the tracked space, the VE rotates the predicted user path into the tracked area without warning (following the computed arc of minimum curvature) causing the user to feel that the VE is spinning around.

Scaled translational gain [9], [10] increases the translational step size of the user in the VE, without modifying rotation by scaling the output of the tracker. Interrante et al. [16] scale the step size of the user. Williams et al. explored three "resetting" methods for manipulating the VE when the user nears the edge of the tracked space [17]. The "resetting" techniques attempt to interfere with virtual experience as minimally as possible. One technique involves turning the HMD off, instructing the user to walk backward to the middle of the laboratory, and then turning the HMD back on. The user will then find herself in the same place in the VE but will no longer be near the edge of the tracked space. The second technique turns the HMD off, asks the user to turn in place, and then turns the HMD back on. The user will then find herself facing the same direction in the VE but facing a different direction in the tracked space. Preliminary research [17] suggests that the most promising of the three techniques uses an audio warning to ask the user to stop and turn 360 degree. The VE rotates at twice the speed of the user and stops rotating after 180 degree. The user is supposed to reorient herself by turning only 180 degree but should think she has turned 360 degree. This ROT attempts to trick the user into not noticing the extra rotation.

Current techniques have characteristics that we believe are likely to cause breaks in presence: audio instructions (unrelated to the content of the VE) and unexpected large rotations of the VE. Our method differs from the current methods in that it does not unexpectedly rotate the VE or use unnatural audio cues. We distract the user with a moving audial, visual, or audial and visual object in the VE. While the user is rotating her head to follow the distractor, the VE is rotated around her. This is similar to a method implemented by Kohli et al. [18] and exploits the imprecision of vestibular perception suggested by Razzaque [7]. We hypothesize that the visual distraction will make the rotation of the VE less noticeable to the user and will not detract from the immersive virtual experience. We conducted a user study to evaluate our method and compare it to the ROTs suggested by Razzaque, Williams, and Nitzsche. Based on the results, we improved our distractor and conducted two follow-on studies to evaluate our improved distractors against the most promising ROTs determined by previous evaluation.

3 METHODS

We conducted three University of North Carolina IRB approved within-subjects user studies to evaluate ROTs and compare distractors to current ROTs. Subjects were different between all experiments. Experiment 1 showed that of the current ROTs, users preferred our method as well as the method suggested by Razzaque [7]. We modified our distractor technique based on user feedback from the first study and then conducted a follow-on study comparing the improved distractor ROT to our original method and to the method suggested by Razzaque [7]. The third study explored improving the visual quality of the distractor as well as adding natural audio to a visual distractor and using audio alone as a distractor.

3.1 Equipment

Each participant wore a Virtual Research Systems V8 head-mounted display (640 $\times$ 480 resolution) tracked using a 3rdTech HiBall 3000. Participants were permitted to walk in an 8 $\times$ 6 m tracked space. The environment used in Experiments 2 and 3 is shown in Fig. 1. A similar environment was used in Experiment 1. All environments were rendered in stereo at 60 fps on a Pentium D dual-core 2.8-GHz processor machine with an NVIDIA GeForce 6800 GPU with 2 Gbytes of RAM. The cardboard taped to the wooden surface was slightly padded and gave users, who had no self-avatar, haptic confirmation of reaching the markers on the paths (Fig. 2).

3.2 Experiment 1

Our first study evaluated the ROTs suggested or implemented in [4], [5], [6], [7], [8], and [17] plus our distractor technique. The measures were *presence*, user-ranked *preference*, and user-ranked *naturalness*.

3.2.1 Participants

Twenty-four introductory psychology students (13 men and 11 women) participated in the experiment. Each subject visited the laboratory once for a session lasting approximately 1 hour and received class credit for participation. All subjects had normal or corrected-to-normal vision and were naive to the purpose of the study. Participants were not informed about ROTs and were initially unaware that the VE would rotate.

3.2.2 Experimental Design

Experiment 1 consisted of two parts, both taking place in the same VE. The VE was an outdoor space featuring a 200-m straight wooden path with circular markers placed 5 m apart along the path. The VE was similar to the environment used in Experiment 2, as shown in Fig. 1. To walk the virtual path, subjects really walked 5 m across the laboratory to a marker, turned 180 degree, and walked back across the laboratory to the next marker. The rotation of the VE occurred only during reorientation. Subjects received audio instructions, via headphones, before the experiment began and received audio trial-specific instructions, via headphones, before each trial. Trial specific instructions included informing subjects to physically turn, turn your head back and forth, or watch the distractor. Subjects did not have a training session and no subject had problems performing the experiment. Subjects were instructed to walk along the path in the environment and to stop at each marker. Once a subject reached a marker, the subject experienced one of four ROTs.

Turn without instruction (T). When the user reaches the marker, the VE immediately rotates 180 degree around the user at 120 degree/second. The rotation relocates the virtual path so it is located within the tracked environment. The user needs to reorient herself in the VE by turning 180 degree. This is similar to the technique described in [4] and [8].

Turn with audio instruction (TI). Audio instructions in the VE, presented via headphones, ask the user to turn 360 degree and continue along the path; however, the VE rotates 180 degree. The rotation of the VE is controlled by the user's head and rotates at twice the speed of the user's head. The user is deceived to think that she has turned 360 degree in both the virtual and real worlds when she has only turned 180 degree in the real world. The user needs to reorient herself in the VE by turning only 180 degree. This is similar to a method described in [17].

Head turn with audio instruction (HT). Audio instructions in the VE, presented via headphones, ask the user to turn her head back and forth and then continue walking along the path. While the user turns her head, the rotation applied to the VE is 1.3 times the rotation speed of the user's head until the VE has rotated 180 degree. The participant reorients herself by rotating 180 degree in the real world. This is similar to a method described in [7].

Head turn with visual instruction, distractor (D). A moving sphere appears in front of the user. The user watches the sphere as it moves in a horizontal arc and continues walking along the path once the sphere disappears. The rotation applied to the VE is 1.5 times the rotation speed of the user's head until the VE has rotated 180 degree. The distractor moves along the arc with sinusoidal displacement, $\text{amplitude} = 0.5\ \text{m}$, and $\text{frequency} = 8\ \text{degree/second}$. The user reorients herself by rotating 180 degree in the real world. The path and velocity of the distractor are described in Fig. 3.

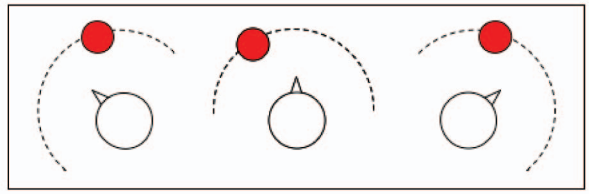

Fig. 3. The path of all distractors is defined as an arc (dashed line) directly in front of the user with sinusoidal displacement along the arc. The distractor moves along the arc causing the subject to turn her head back and forth to keep the distractor in view. The distractor is displayed 1.75 m away from the user, and the height of all distractors is approximately 0.5 m. The same path trajectory is used for all distractors in each of the three experiments.

All rotation rates were determined from pilot experiments. For all ROTs, the rotation of the VE is increased only when the direction the head is turning is in the same direction the VE is rotating.

Part I of the experiment assessed the user's subjective sense of presence in the environment and consisted of four trials, each using one of the four ROTs. The order of the trials was counterbalanced among subjects. Each trial was comprised of four subtrials in which the subject walked along the virtual path and stopped at markers along the path. When the subject reached a marker, an ROT would stop the subject and rotate the VE. Each trial consisted of walking to four markers and experiencing the same ROT four times. Subjects then removed the HMD and filled out a modified Slater-Usoh-Steed (SUS) presence questionnaire [19], [20].

Part II consisted of 12 trials, each with two ROTs. Trials were counterbalanced and every ROT was compared to every other ROT twice, with order reversed, to remove the possibility of order effects. Each trial required the subject to walk to a marker, experience an ROT, then walk to the next marker, and experience a different ROT. The subject then made a forced choice regarding which ROT they preferred and which ROT was most natural. At the end of each trial, subjects were asked by the experimenter to explain why they chose one ROT over another.

At the end of the experiment, subjects filled out an exit survey and were asked to describe the differences between the four ROTs, explain what they liked or disliked about each of the ROTs, and rank the four ROTs based on naturalness and preference.

We used a modified SUS presence questionnaire [19], [20] to assess the user's subjective sense of presence. Naturalness and preference were each measured in two ways: at the end of the experiment, subjects ranked the ROTs, and during the experiment, subjects made a forced-choice ranking between pairs of ROTs.

TABLE 1
Experiment 1—Mean HIGH Scores on SUS Presence Questionnaire

ROT	$\bar{x}$
D	0.47917
HT	0.50000
TI	0.28472
T	0.44444

TABLE 2
Experiment 1—Results of Logistic Regression of SUS Presence Questionnaire

Contrast	$\chi^2(1)$	$p(\alpha = 0.05)$
D vs. HT	0.15	0.6980
D vs. TI	3.35	0.0672
D vs. T	0.02	0.8912
HT vs. TI	11.97	$\boxed{0.0005}$
HT vs. T	0.46	0.4986
T vs. TI	6.39	$\boxed{0.0115}$

Statistically significant results are marked with a box.

D - Distractor
HT - Head turn with audio instruction
TI - Turn with audio instruction
T - Turn without instruction

Fig. 4. Experiment 1—legend.

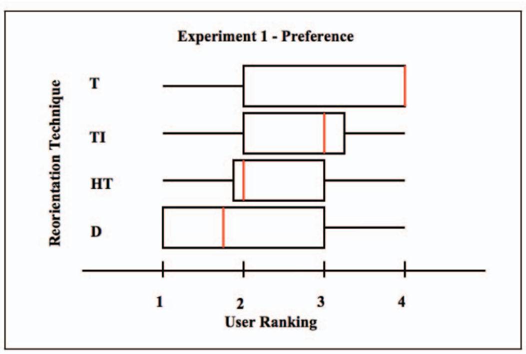

Fig. 5. Experiment 1—user rated preference scores from 1 (most preferred) to 4 (least preferred). Standard box-and-whisker plots with the median in red.

3.2.3 Results

Tables 1 and 2 and Figs. 4, 5, 6, 7, and 8 show our results from Experiment 1. The SUS presence scores were analyzed using the same binomial logistic regression techniques as applied in previous uses of the questionnaire [1]. The response to each question was converted from the 1 to 7 scale to a binary value: responses of 5, 6, or 7 were converted to HIGH (1) and values less than 5 were converted to LOW (0). This conversion avoids treating the subjective ratings as interval data. After this conversion, we further transformed the data to create a new response variable for each participant: the count of their HIGH responses. Tables 1 and 2 show the average proportion of HIGH responses for each of the four conditions as well as the pairwise contrasts of conditions using logistic regression adjusted for multiple observations for each participant. There is a statistically significant effect

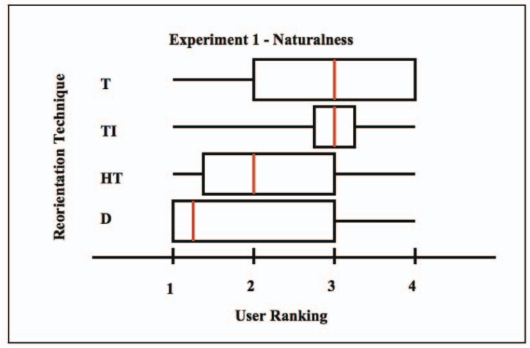

Fig. 6. Experiment 1—user rated naturalness scores from 1 (most natural) to 4 (least natural). Standard box-and-whisker plots with the median in red.

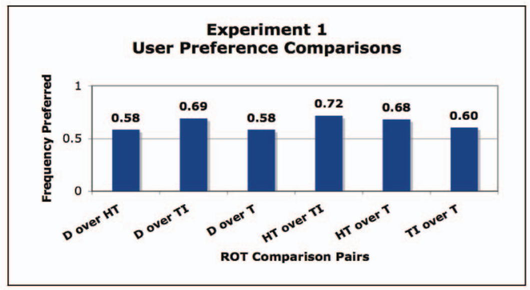

Fig. 7. Experiment 1—user forced-choice comparisons of preference across ROTs.

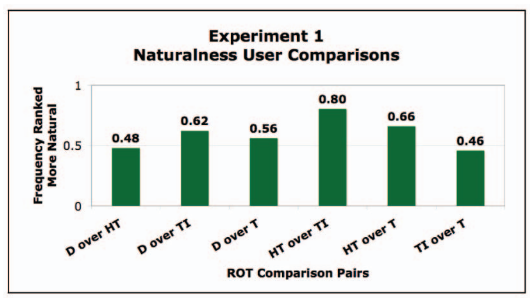

Fig. 8. Experiment 1—user forced-choice comparisons of naturalness across ROTs.

between HT versus TI ($\chi^2(1) = 11.97, p < 0.05$) and T versus TI ($\chi^2(1) = 6.39, p < 0.05$). We also found a trend between D versus TI ($\chi^2(1) = 3.35, p = 0.0672$).

Figs. 5 and 6 show the average user rankings, with 1 being the highest and 4 being the lowest, of preference and naturalness by ROT, respectively. The data were analyzed using Friedman's ANOVA. User-ranked naturalness was significantly different between ROTs: $\chi^2(3) = 9.524, p < 0.05$, as was user-ranked preference ($\chi^2(3) = 10.958, p < 0.01$). Wilcoxon tests were used to expand on this finding and a Bonferroni correction was applied. All effects are reported at a 0.0125 level of significance. The Wilcoxon test statistic is T' and should not be confused with our condition T. Subjects significantly found HT to be more natural than TI ($T' = 220.00, r = 0.38$) and significantly preferred D and HT to T, $T' = 237.50$, $r = 0.37$ and $T' = 235.50$, $r = 0.36$, respectively.

Figs. 7 and 8 show user preference and user-ranked naturalness of paired ROTs. The frequency at which a subject preferred one ROT over another was compared to random choice, a frequency of 0.50, using Wilcoxon tests. We found subjects significantly preferred D over TI ($T' = 184.00$, $p < 0.05, r = 0.31$), HT over TI ($T' = 176.00, p < 0.05$, $r = 0.35$), and HT over T ($T' = 165, p < 0.5, r = 0.28$) and subjects significantly considered HT to be more natural than TI ($T' = 170.00, p < 0.01, r = 0.50$).

3.2.4 Discussion

Subjects' exit surveys and responses during the experiment provided useful information about each ROT. Subjects' reasons for favorably rating ROTs included: the method provided instruction (either audio or visual), they did not notice rotation, and the method was realistic or natural. We believe that D and HT were rated higher by subjects than T and TI because both rotate the VE while the subject is stimulating the vestibular system by turning her head and is less likely to notice the rotation of the VE.

We found subjects were confused during the first few subtrials of T and often needed extra instruction from the experimenter to determine which direction to walk in the laboratory. After the first subtrial of T, one subject exclaimed, "Where am I?" and had to be stopped before walking out of the laboratory space. This occurred with several subjects; however, after three subtrials subjects often no longer needed extra instruction to determine the correct direction to walk in the laboratory. Subjects described T as dizzying and complained about having no orientation in the VE after the world "spun." Some subjects found T to be "fun" and simple because the subject just waited for "the flip" and then the virtual world moved as they expected.

Subjects were occasionally confused by the audio instructions in TI asking for the subject to turn 360 degree but seeing the VE stop rotating after the subject only turned 180 degree. Subjects would occasionally turn 360 degree in the real world and then turn an additional 180 degree to walk the correct direction along the path. Subjects also noticed the VE spinning at a much faster rate than they were turning. One subject complained about the disembodied voice that did not fit into the environment. Subjects praised this technique for giving them some control over the VE by spinning when the subject turned and subjects also found audio instructions helpful for determining how to turn around in the VE.

When using HT, subjects complained about noticing the path in VE not being in the right place once they started turning their heads but also commented on not seeing the rotation as much as other ROTs. Some subjects would occasionally stop turning their heads before the VE had rotated 180 degree and would stand and wait until given more instruction to continue turning their heads. These subjects would no longer need extra instruction after three subtrials. Subjects liked having control over the rotation of the VE that was offered by turning their heads.

Subjects commented that the distractor was dizzying because it moved too fast, or that they would not be able to turn their heads fast enough to keep it in view. Subjects also complained that a "big red ball is not normal." Some subjects also complained about the ball's sudden appearance and disappearance. Other subjects found D entertaining and engaging and found that when looking at the ball they were not paying attention to the moving scenery.

Fig. 9. Butterfly used in Experiment 2.

Our results revealed that D and HT were better ROTs than TI and T by producing increased presence, having higher user preference and being more natural to the user. However, user feedback suggested further improvements that were explored in Experiment 2.

3.3 Experiment 2

Based on the results and user feedback from Experiment 1, we improved our distractor method by using a butterfly instead of a sphere because it is more natural for the VE being used. The butterfly model is shown in Fig. 9. We also had the butterfly fly in and out of the VE instead of suddenly appearing and disappearing, a common user complaint about the distractor from Experiment 1. We compared our improved distractor to the most promising ROTs from Experiment 1: our original red sphere distractor and head turn with audio instruction [7].

To have the butterfly appear more lifelike and due to the complaints from Experiment 1 that the distractor was "dizzying," we slowed the speed at which the butterfly flew around the subject. To compare the difference in natural versus unnatural distractors, we also changed the speed of the sphere to match that of the butterfly.

3.3.1 Participants

Twelve participants (six men and six women), mostly computer science graduate students in their 20s, participated in the experiment. Each subject visited the laboratory once for a session lasting approximately 1 hour and received \$7.50 for participation during the week and \$10.00 for weekend participation. All subjects had normal or corrected-to-normal vision and were naive to the purpose of the study. Participants were not informed about ROTs and were initially unaware that the VE would rotate.

3.3.2 Experimental Design

Experiment 2 consisted of two parts, both taking place in the same VE. The VE was an outdoor space similar to Experiment 1, with a 180-m straight wooden path and square markers placed 5 m apart along the path. The environment is shown in Fig. 1. Subjects were instructed to walk along the designated path in the environment and to

TABLE 3
Experiment 2—Mean Percentage of HIGH Scores on SUS Presence Questionnaire

ROT	$\bar{x}$
ID	0.52778
D	0.45833
HT	0.41667

ID - Improved distractor
D - Distractor
HT - Head turn with audio instruction

Fig. 10. Experiment 2—legend.

stop at each marker along the path. Once a subject had reached a marker, the subject experienced one of three ROTs.

Head turn with audio instruction (HT). Audio instructions in the VE, presented via headphones, ask the user to turn her head back and forth and then continue walking along the path. While the user turns her head, the rotation applied to the VE is 1.3 times the rotation speed of the user's head until the VE has rotated 180 degree. The participant reorients herself by rotating 180 degree in the real world. This is similar to a method described in [7].

Head turn with visual instruction, distractor (D). A moving sphere appears in front of the user. The user watches the sphere as it moves in a horizontal arc and continues walking along the path once the sphere disappears. The rotation applied to the VE is 1.5 times the rotation speed of the user's head until the VE has rotated 180 degree. The distractor moves along the arc with sinusoidal displacement, $\text{amplitude} = 0.5\ \text{m}$, and $\text{frequency} = 2$ degree/second. The user reorients herself by rotating 180 degree in the real world. The path and velocity of the distractor are described in Fig. 3.

Head turn with visual instruction, improved distractor (ID). A butterfly flies into the scene toward the subject and then flies in a horizontal arc in front of the subject. The subject continues walking along the path once the butterfly flies away. While the user is watching the butterfly, the rotation applied to the VE is 1.5 times the rotation speed of the user's head until the VE has rotated 180 degree. The distractor moves along the arc with sinusoidal displacement, $\text{amplitude} = 0.5\ \text{m}$, and $\text{frequency} = 2$ degree/second. The user reorients herself by rotating 180 degree in the real world.

Part I of the experiment assessed the user's subjective sense of presence, how aware the user was of turning around, and how aware the user was of the VE rotation. Part I consisted of three trials, each using one ROT. The order of the trials was counterbalanced among subjects. Each trial was comprised of eight subtrials requiring the subject to walk along the virtual path to the next marker along the path. Once the subject reached a marker, an ROT would stop the subject and rotate the VE. Each trial consisted of walking to eight markers, experiencing the same ROT eight times. Subjects then removed the HMD and filled out the SUS presence questionnaire. In addition to the presence questionnaire, subjects also answered the following question.

Did you notice anything unnatural or odd during your virtual experience? Please rate the following on a scale from 0 to 7, where $0 =$ did not notice or happen, $7 =$ very obvious and took away from my virtual experience.

- ___I felt like I was turning around.
- ___I saw the virtual world get smaller or larger.
- ___I saw the virtual world flicker.
- ___I saw the virtual world rotating.
- ___I felt like I was getting bigger or smaller.
- ___I saw the virtual world get brighter or dimmer.

We embedded questions of interest, those about the VE rotating and the subject turning and analyzed only the results for those questions.

Part II consisted of six trials, each with two ROTs. Trials were counterbalanced and each ROT was compared to every other ROT twice with order reversed to remove the possibility of order effects. Each trial required the subject to walk to a marker, experience an ROT, and then walk to the next marker and experience a different ROT. The subject then made a forced-choice decision as to which ROT they preferred and which ROT was most natural. Subjects were also asked to explain why they chose one ROT over another.

At the end of the experiment, subjects filled out an exit survey and ranked the three ROTs based on naturalness and preference.

3.3.3 Results

Tables 3 and 4 and Figs. 10, 11, 12, 13, 14, and 15 show our results from Experiment 2. The analysis of the SUS presence scores was done in the same manner as reported in Section 3.2.3. Tables 3 and 4 show the proportion of HIGH responses for each of the three conditions and the results of the pairwise contrasts of conditions. We found no statistical significance with user reported presence scores between ROTs.

TABLE 4
Experiment 2—Results of Logistic Regression of SUS Presence Questionnaire

Contrast	$\chi^2(1)$	$p(\alpha = 0.05)$
ID vs. D	1.09	0.2974
ID vs. HT	1.72	0.1895
D vs. HT	0.63	0.4291

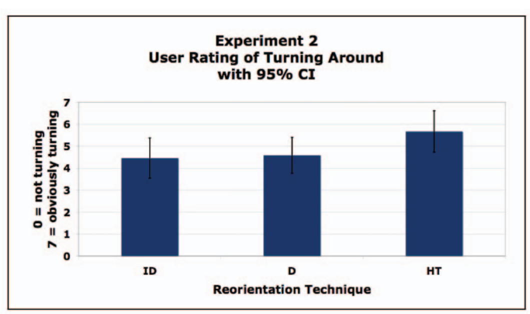

Fig. 11. Experiment 2—user rating: "I felt like I was turning around."

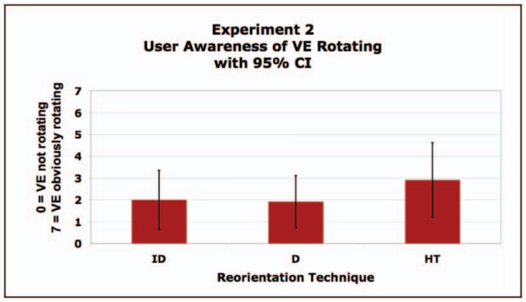

Fig. 12. Experiment 2—user rating: “I saw the virtual world rotating.”

Fig. 11 shows average user scores by ROT of response to the question about feeling like they were turning around. We analyzed the data using Friedman’s ANOVA and found significant differences between ROTs: $\chi^2(2) = 7.550$, $p < 0.05$. Wilcoxon tests were used to follow up this finding. A Bonferroni correction was applied and all effects are reported at a 0.025 level of significance. Subjects significantly felt like they were turning more in HT than D ($T' = 51.50$, $r = 0.74$), and a trend was found with subjects feeling like they were turning more in HT than ID ($T' = 46.50, r = 0.56$).

Fig. 12 shows average user scores by ROT of response to the question about subjects noticing that the VE was rotating. Using Friedman’s ANOVA, we found no significant difference between ROTs: $\chi^2(2) = 3.630$, $p = 0.187$.

Figs. 13 and 14 show results from user ranked preference and naturalness by ROT, with 1 being the highest preference and 3 being the lowest. Trends were found between ROTs and subject rankings of preference ($\chi^2(2) = 4.667, p = 0.108$) and subject-ranked naturalness ($\chi^2(2) = 5.167, p = 0.080$).

Fig. 15 shows user preference and user-ranked naturalness of paired ROTs. The frequency at which a subject preferred one ROT over another was compared to random choice, a frequency of 0.50, using Wilcoxon tests. Subjects preferred both ID and D to HT ($T' = 65.00$, $r = 0.47$, and $T' = 77.00$, $r = 0.51$, respectively) and ranked ID and D to be more natural than HT ($T' = 82.50$, $r = 0.44$, and $T' = 65.00$, $r = 0.47$, respectively). A trend suggests that ID is more natural than D ($T' = 63.00, r = 0.28, p = 0.11$).

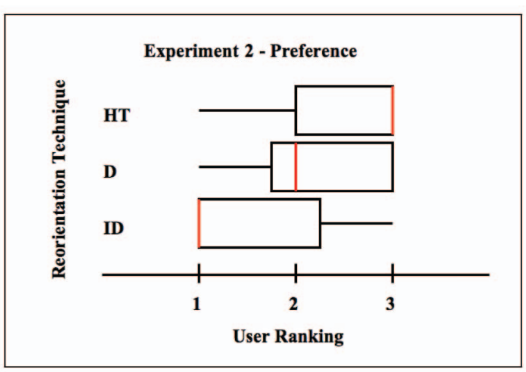

Fig. 13. Experiment 2—user rated preference scores from 1 (most preferred) to 3 (least preferred). Standard box-and-whisker plots with the median in red.

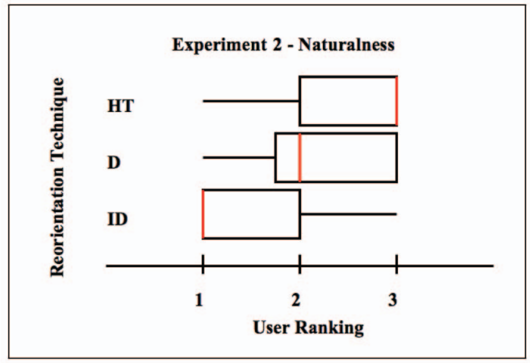

Fig. 14. Experiment 2—user rated naturalness scores from 1 (most natural) to 3 (least natural). Standard box-and-whisker plots with the median in red.

3.3.4 Discussion

The results from Experiment 2 suggest ROTs that use distractors reduce the likeness of a users’ feeling as if they are turning around while being reoriented. The results also suggest that subjects prefer ROTs with distractors and consider them to be more natural. We account for the difference between D and HT in Experiment 2 compared to Experiment 1 by the reduced speed of the sphere from 8 degree/second to 2 degree/second.

The VE rotates 1.3 times the rotation speed of the user’s head in HT and 1.5 times the rotation speed of the user’s head in D and ID. This difference in VE rotation relative to head turn speed may explain why there was no significant difference between ROTs and user awareness of the VE rotating. Further studies comparing different rotation speeds of the VE relative to head turn speeds may reveal further differences between ROTs with and without distractors.

Exit surveys and responses during Experiment 2 again provided useful information about each ROT. In the HT condition subjects found turning their heads back and forth for no reason to be annoying and “silly.” One subject noted, “The voice destroys being there.” Subjects were aware that the path had moved when they rotated their heads and complained of being more lost than with visual instruction. Two subjects found HT to provide more freedom and the ability to look around the environment during reorientation.

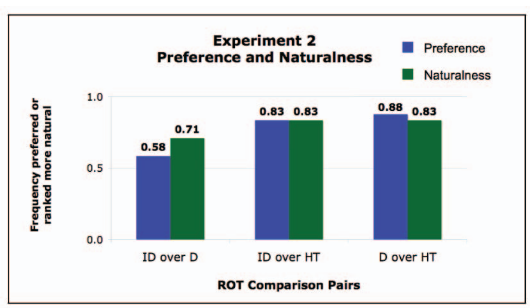

Fig. 15. Experiment 2—user forced-choice comparisons of preference and naturalness across ROTs.

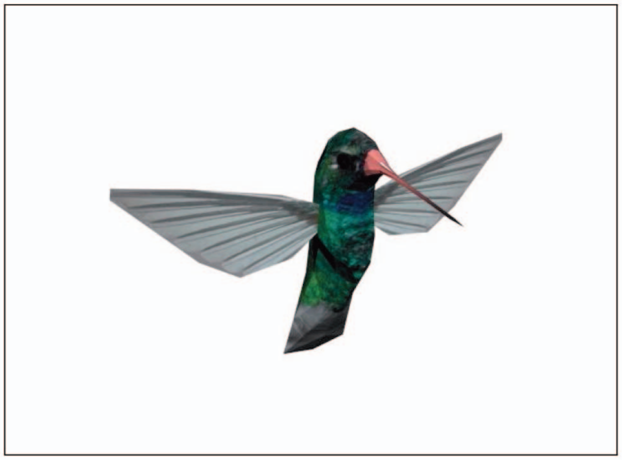

Fig. 16. Hummingbird used in Experiment 3.

Subjects found D to be easy to follow and some subjects found D less distracting than the flapping butterfly wings of ID. Subjects continued to complain about the sphere not being natural to the environment and noted that it "defies the laws of physics." Subjects commented on the naturalness of the butterfly, but some found the flapping of the butterfly wings to be "annoying." Subjects enjoyed watching the butterfly fly in and out of the scene but, in Experiment 2, no negative comments were made about the sudden appearance and disappearance of the sphere. Based on the numerous complaints about the sudden appearance and disappearance of the sphere in Experiment 1, we believe the distractor should engage the user in a manor natural to the scene.

3.4 Experiment 3

Based on user feedback from Experiment 2, we improved our distractor method by using a more realistic model: a hummingbird (Fig. 16). In addition to using a more realistic model created using a realistic texture map and modeled by an artist, we explored adding sound to our visual distractor and using sound alone as a distractor. All distractors in this experiment had the same motion path and speed of the butterfly from Experiment 2.

3.4.1 Participants

Twelve participants, mostly graduate students and researchers (seven men and five women) participated in the experiment. The age range was 23 to 50, with an average age of 32. Each subject visited the laboratory once for a session lasting approximately 1 hour and received $7.50 for participation during the week and $10.00 for weekend participation. All subjects had normal or corrected-to-normal vision and were naive to the purpose of the study. Participants were not informed about ROTs and were initially unaware that the VE would rotate.

3.4.2 Experimental Design

Experiment 3 consisted of two parts, both taking place in the same VE. The VE was the same as Experiment 2 and consisted of a 180-m straight wooden path with square markers placed 5 m apart along the path. Subjects were instructed to walk along the path in the environment and to stop at each marker along the path. Upon reaching each marker, the subject experienced one of three ROTs.

Distractor, visual (DV). A hummingbird flies into the scene toward the subject and then flies in a horizontal arc in front of the subject. The subject continues walking along the path once the hummingbird flies away. While the user is watching the hummingbird, the rotation applied to the VE is 1.5 times the rotation speed of the user's head until the VE has rotated 180 degree. The distractor moves along the arc with sinusoidal displacement, $\mathrm{amplitude} = 0.5\ \mathrm{m}$, and $\mathrm{frequency} = 2$ degree/second. The user reorients herself by rotating 180 degree in the real world.

Distractor, visual and audio (DVA). A hummingbird flies into the scene toward the subject and then flies in a horizontal arc in front of the subject. The hummingbird is accompanied by spatialized audio of hummingbird wings flapping, presented via headphones. The hummingbird has sinusoidal displacement along the arc, $\mathrm{amplitude} = 0.5\ \mathrm{m}$, and $\mathrm{frequency} = 2$ degree/second. The subject continues walking along the path once the hummingbird flies away. While the user is watching the hummingbird, the rotation applied to the VE is 1.5 times the rotation speed of the user's head until the VE has rotated 180 degree. The user reorients herself by rotating 180 degree in the real world.

Distractor, audio (DA). A sound of hummingbird wings flapping flies into the scene toward the subject and then spatially moves in a horizontal arc in front of the subject. The sound has sinusoidal displacement along the arc, $\mathrm{amplitude} = 0.5\ \mathrm{m}$, and $\mathrm{frequency} = 2$ degree/second. There is no visual hummingbird to accompany the sound. The subject continues walking along the path once the sound of the hummingbird flies away. While the user is listening to the hummingbird, the rotation applied to the VE is 1.5 times the rotation speed of the user's head until the VE has rotated 180 degree. The user reorients herself by rotating 180 degree in the real world.

Experiment 3 had the same experimental design as Experiment 2. Part I of the experiment assessed the user's subjective sense of presence, how aware the user was of turning around, and how aware the user was of the VE rotation. Part I consisted of three trials, each using one ROT. The order of the trials was counterbalanced among subjects. Each trial was comprised of eight subtrials requiring the subject to walk along the virtual path to the next marker along the path. Once the subject reached a marker, an ROT would stop the subject and rotate the VE. Each trial consisted of walking to eight markers, experiencing the same ROT eight times. Subjects then removed the HMD and filled out the SUS presence questionnaire. In addition to the presence questionnaire, subjects also answered the embedded questions about the VE rotating and the user turning around that were presented in Experiment 2.

Part II consisted of six trials, each with two ROTs. Trials were counterbalanced and every ROT was compared to every other ROT twice with order reversed to remove possible order effects. Each trial required the subject to walk to a marker, experience an ROT, and then walk to the next marker and experience a different ROT. The subject then made a forced-choice decision as to which ROT they

TABLE 5
Experiment 3—Mean Percentage of HIGH Scores on SUS Presence Questionnaire

ROT	$\bar{x}$
DV	0.77780
DA	0.62500
DVA	0.69444

TABLE 6
Experiment 3—Results of Logistic Regression of SUS Presence Questionnaire

Contrast	$\chi^2(1)$	$p(\alpha = 0.05)$
DV vs. DA	6.23	$\boxed{0.0126}$
DV vs. DVA	1.60	0.2060
DVA vs. DA	1.99	0.1581

Statistically significant results are marked with a box.

DV - Distractor, visual
DVA - Distractor, visual and audio
DA - Distractor, audio

Fig. 17. Experiment 3—legend.

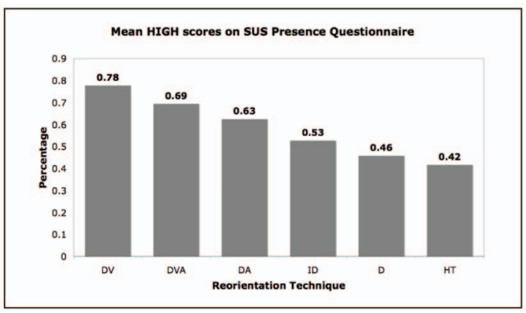

Fig. 18. Experiments 2 and 3—user rating: Mean percentage of HIGH scores on SUS Presence Questionnaire.

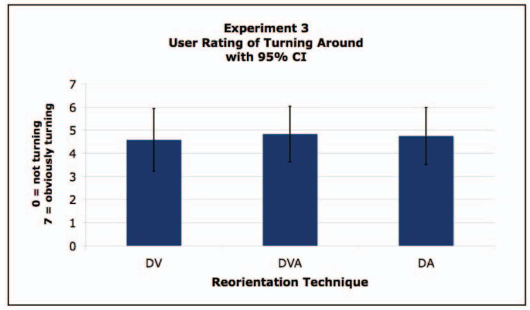

Fig. 19. Experiment 3—user rating: "I felt like I was turning around."

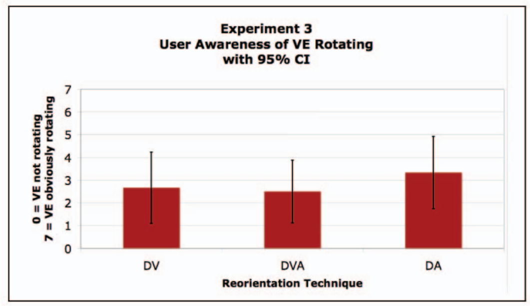

Fig. 20. Experiment 3—user rating: "I saw the virtual world rotating."

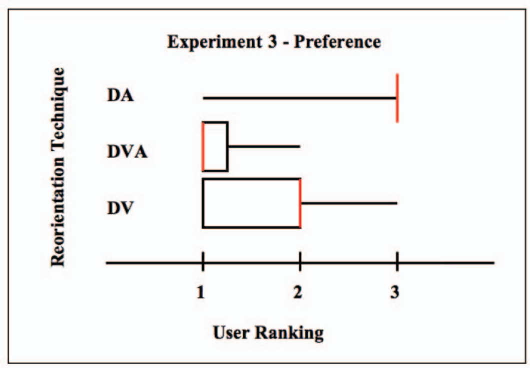

Fig. 21. Experiment 3—user rated preference scores from 1 (most preferred) to 3 (least preferred). Standard box-and-whisker plots with the median in red.

preferred and which ROT was more natural. Subjects were also asked to explain why they chose one ROT over another.

At the end of the experiment, subjects filled out an exit survey and ranked the three ROTs based on naturalness and preference.

3.4.3 Results

Tables 5 and 6 and Figs. 17, 18, 19, 20, 21, 22, and 23 show the results from Experiment 3. The analysis of the SUS presence scores was performed in the same manner as reported in Section 3.2.3. Tables 5 and 6 show the proportion of HIGH responses for each of the three conditions and the results of the pairwise contrasts of conditions. We found users felt significantly more present in DV than DA $(\chi^2(1) = 6.23, p < 0.05)$.

Experiments 2 and 3 used an identical experimental design: participants perform the same number of trials and used the same environment. Also, subjects for both experiments were mostly computer scientists and researchers. Since the subjects came from the same pool, we were able to compare presence scores between Experiment 2 and Experiment 3. Table 7 and Fig. 18 show the proportion of HIGH responses for each of the three conditions and the results of the pairwise contrasts of conditions. We found users felt significantly more present in DV than ID, D, and HT ($\chi^2(1) = 6.18$, $p < 0.05$, $\chi^2(1) = 10.73$, $p < 0.01$, $\chi^2(1) = 10.44$, $p < 0.01$, respectively). Users statistically felt more present in DVA than D and HT ($\chi^2(1) = 7.76$, $p < 0.01$, $\chi^2(1) = 9.06$, $p < 0.01$, respectively), and a trend suggests that users feel more present in DVA than ID $(\chi^2(1) = 3.29, p = 0.07)$. Users also felt significantly more present in DA than D and HT ($\chi^2(1) = 3.84$, $p = 0.05$, $\chi^2(1) = 6.60$, $p < 0.05$, respectively).

Fig. 19 shows average scores of response to the question about feeling like they were turning around for each ROT. We analyzed the data using Friedman's ANOVA and found no significant differences between ROTs: $\chi^2(2) = 0.712$, $p = 0.514$.

Using Friedman's ANOVA, we found no significant difference between ROTs and subjects noticing that the VE (Fig. 20) was rotating $\chi^2(2) = 1.372$, $p = 0.298$.

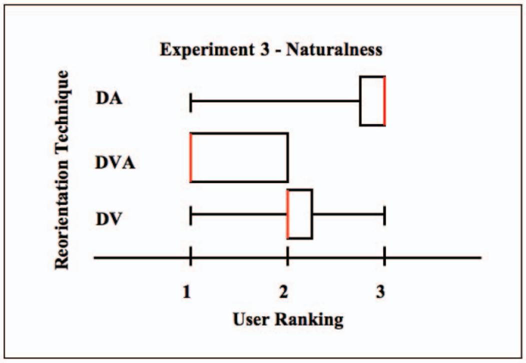

Fig. 22. Experiment 3—user rated naturalness scores from 1 (most natural) to 3 (least natural). Standard box-and-whisker plots with the median in red.

TABLE 7
Experiments 2 and 3—Results of Logistic Regression of SUS Presence Questionnaire

Contrast	$\chi^2(1)$	$p(\alpha = 0.05)$
DV vs. ID	6.18	$\boxed{0.0129}$
DV vs. D	10.73	$\boxed{0.0011}$
DV vs. HT	10.44	$\boxed{0.0012}$
DVA vs. ID	3.29	0.0699
DVA vs. D	7.76	$\boxed{0.0053}$
DVA vs. HT	9.06	$\boxed{0.0026}$
DA vs. ID	1.09	0.2969
DA vs. D	3.84	$\boxed{0.0500}$
DA vs. HT	6.60	$\boxed{0.0102}$

Statistically significant results are marked with a box.

Figs. 21 and 22 show the subjects' naturalness and ranked preference of ROTs with 1 being the highest rank and 3 being the lowest. We found significant differences between ROTs of subject-ranked preference ($\chi^2(2) = 16.875, p < 0.05$) and subject-ranked naturalness ($\chi^2(2) = 102.308, p < 0.001$). Wilcoxon tests were used to follow up this finding. A Bonferroni correction was applied and all effects are reported at a 0.025 level of significance. Subjects significantly preferred DVA to DV and DA ($T' = 66.00$, $r = 0.352$, and $T' = 75.50$, $r = 0.433$, respectively), and a trend was found with subjects preferring DV to DA ($T' = 62.00, r = 0.306$). Subjects ranked DVA to be more natural than DV and DA ($T' = 66.00$, $r = 0.387$, and $T' = 72.00$, $r = 0.342$, respectively).

Fig. 23 shows user preference and user-ranked naturalness of paired ROTs. The frequency at which a subject preferred one ROT over another was compared to random choice, a frequency of 0.50, using Wilcoxon tests. Subjects preferred DVA to both DV and DA ($T' = 55.00$, $r = 0.575$, and $T' = 55.00$, $r = 0.575$, respectively). Subjects also preferred DV to DA ($T' = 60.00, r = 0.45$). Subjects ranked DVA to be more natural than both DV and DA ($T' = 55.00$, $r = 0.575$, and $T' = 54.00$, $r = 0.352$, respectively).

3.4.4 Discussion

The results from Experiment 3 suggest that users felt increased presence with a realistic visual distractor without audio than with only an audio distractor. We performed contrasts between Experiments 2 and 3 and found that improving the visual quality of the distractor from an unrealistic butterfly to a more realistic hummingbird produced a higher feeling of presence among users. Note that the motion path and animation of the distractors was not modified between Experiments 2 and 3. Our results suggest that using more realistic distractors can increase a user's feeling of presence.

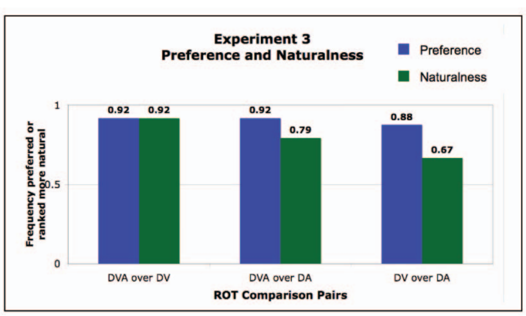

Fig. 23. Experiment 3—user forced-choice comparisons of preference and naturalness across ROTs.

Adding natural audio sounds to a visual distractor resulted in no significant increase of user-reported presence when compared to a visual distractor without audio. However, users prefer the addition of audio cues to the visual distractor and find the audio plus visual stimuli to be more natural than visual or audio alone. Many users claimed that the hummingbird with the sound of wings flapping stimulated more senses and was therefore more natural. No significant change in user-reported presence was found when the visual cue of the hummingbird was removed and only the 3D audio cues were presented to the user.

When comparing presence data from Experiment 2 and Experiment 3, we found that natural audio as a distractor without visual cues produces a higher sense of presence than using the unnatural red sphere distractor from Experiment 2. The ability to use only audio as a distractor extends the range of VEs in which distractors are applicable. Possible applications for audio distractors include military applications where environment appropriate moving visual objects in front of the user are not possible. Military training applications may have loud noises or explosions that naturally suit the environment and can be used as distractors. However, further studies need to be conducted to determine if distractors cause mistraining in military applications. Audio distractors may be useful for VEs because they do not require model changes and modeling and animation expertise.

One user commented that the audio distractor was hard to track and while he was searching to find the (audio) hummingbird, he was much less aware of the VE rotating. Other users found the audio frustrating because they had a hard time determining where the hummingbird was located. This may be the reason that users ranked the audio distractor lower than the distractors with a visual hummingbird. Users may prefer natural distractors with audio to audio distractors, but audio distractors may still be effective.

4 Conclusion

We have successfully implemented and tested eight ROTs to handle the worst-case scenario in large walking VEs—when the user is about to walk out of the tracked space. Five of these

ROTs use a novel technique, distractors—objects in the VE that the user focuses on while the VE rotates—to minimize the observed rotation of a VE during reorientation. In addition to reducing observed rotation of the VE, ROTs using distractors were preferred and ranked more natural by users than currently available ROTs that do not use distractors. We also found subjects were less aware of physically turning around in the VE when reorienting using distractors.

Based on user feedback, ROTs should be realistic and the user should not notice the rotation of the VE. Unlike nondistractor ROTs, distractors can be realistic and our results suggest distractors reduce the likelihood of perceiving VE rotation during reorientation. Distractors should also exhibit smooth movements that are easy and interesting to watch. Improving the realism of the distractor increases a user's feeling of presence and adding natural audio to a visual distractor is preferred and considered more natural to users than using a visual or audio distractor alone.

An audio distractor does not produce as high a feeling of presence as a natural audio-visual distractor; however, it does produce a higher feeling of presence than an unnatural distractor without audio. Audio distractors can be easier to implement than visual distractors as they require so model changes. Audio distractors may also be useful for VEs in which the addition of visual distractors may be unnatural or detract from the VE experience.

We believe that optimal distractors are VE-dependent and should be designed to be as natural as possible to the VE. Possible implementations of distractors include: exploring a virtual house and having a dog run by, walking through a virtual art museum and having a docent point you in a new direction, and training dismounted infantry to successfully navigate enemy territory while snipers are heard in the distance.

Distractors allow users to move by really walking in VEs that are larger than the tracked laboratory space; however, further investigation is needed to determine the potential effects of using distractors. Potential future work includes examining cognitive load effects that may hinder training applications and exploring speed, appearance, and motion paths of distractors. Other areas of research include comparing really walking with distractors to other virtual locomotion systems such as walking-in-place and flying that also allow users to explore large virtual spaces.

Acknowledgments

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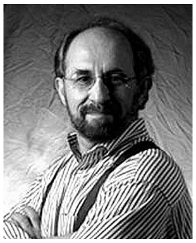

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