Walking > Walking-in-Place > Flying, in Virtual Environments

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Abstract

A study by Slater, *et al.*, [1995] indicated that naive subjects in an immersive virtual environment experience a higher subjective sense of presence when they locomote by walking-in-place (*virtual walking)* than when they push-button-fly (along the floor plane). We replicated their study, adding real walking as a third condition.

Our study confirmed their findings. We also found that real walking is significantly better than both virtual walking and flying in ease (simplicity, straightforwardness, naturalness) as a mode of locomotion. The greatest difference in subjective presence was between flyers and both kinds of walkers. In addition, subjective presence was higher for real walkers than virtual walkers, but the difference was statistically significant only in some models. Follow-on studies show virtual walking can be substantially improved by detecting footfalls with a head accelerometer.

As in the Slater study, subjective presence significantly correlated with subjects' degree of association with their virtual bodies (avatars). This, our strongest statistical result, suggests that substantial potential presence gains can be had from tracking all limbs and customizing avatar appearance.

An unexpected by-product was that real walking through our enhanced version of Slater's visual-cliff virtual environment (Figure 1) yielded a strikingly compelling virtual experience—the strongest we and most of our visitors have yet experienced. The most needed system improvement is the substitution of wireless technology for all links to the user.

CR Categories and Subject Descriptors: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism — *Virtual Reality*; I.3.6 [Computer Graphics]: Methodology and Techniques — *Interaction techniques*; H.5.2 [Information Interfaces]: User Interfaces — *Evaluation/Methodology*.

Keywords: Presence, Locomotion, Virtual Reality, Virtual Walking, Human Factors, Neural Networks, Visual Cliff

Figure 1. View over virtual ledge.

1. BACKGROUND AND OBJECTIVES

A crucial problem in virtual environments research is the development of natural and effective virtual surrogates for user interactions with physical spaces and objects. Locomotion through virtual spaces is the most primitive and important special case [Iwata, 1999; Bowman, 1997].

Most people believe, and studies confirm, that active usage of the participant's body, with the real proprioceptive sensations matched by synthetic visual and aural data, strongly affects virtual presence [Slater, 1994; Slater, 1997]. Therefore research in locomotion has proceeded in two dimensions: development of wide-area trackers so users can really walk about [Ward, 1992], and development of body-active surrogates for walking: treadmills, bicycles, wheelchairs, roller skates, and walking-in-place [Brooks, 1986; Christensen, 1998; Darken, 1997; Iwata, 1999; Slater, 1993].

In immersive virtual environments the most common mode of locomotion is local walking limited by tracker range, combined with button-controlled flying of the whole local neighborhood to a different virtual location [Robinett, 1992]. This can be likened to walking about on a flat-bed truck that is independently navigated for global motions. Slater, *et al.*, developed a simple and economical walk-in-place technique, a *virtual treadmill*, that uses a neural net to analyze the tracked head motion to detect steps [Slater, 1993; Hertz, 1991]. A 1995 study indicated that virtual walking using this technique significantly enhanced the subjective rating of presence compared to flying, for subjects who subjectively associated with their avatars. Avatar association did not significantly enhance presence for flying subjects [Slater, 1995].

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In the present study we brought the two streams of locomotion research together, using a wide-area ceiling tracker and replicating the Slater 1995 study of virtual walking, and adding real walking as a third condition.

The objectives were:

- To see if the results of the earlier study hold true, given more recent technology.
- To compare flying, virtual walking, and real walking with respect to ease of locomotion and subjective presence.

If virtual walking is indeed better than flying, it is so economical to implement as to become the technique of choice for most applications that today use flying. If, and this was our hope, virtual walking is essentially equivalent to real walking, wide-area tracking can be reserved for very specific applications where physical motion is essential.

2. ENHANCEMENTS TO THE ORIGINAL STUDY

We tried to maintain the integrity of the original study. However, we amended the procedure and scenario to accommodate restrictions of physical space and to add real walking, improve the visual fidelity of the model, and enhance the measure of presence.

2.1 Real Walking

Participants were free to walk around the entire virtual scene in the same manner as in a real environment. We tracked the user's head and one hand using a custom optical tracker [Ward, 1992; Welch, 1997]. This tracker works over a range of approximately 10 m by 4 m with millimeter precision. Two optical sensors view blinked infrared LEDs on the ceiling tiles. The tracking system updates position and orientation at approximately 1.5 kHz. These reports are fed to the application at 70 Hz. We set tracker filtering to result in tracker latency of 25 ms. Total latency, taking into account network and graphics delays as well, was approximately 100 ms. Allowing participants to walk freely around a large area required care so that participants would not snag or trip on cables, or collide with real obstacles in the laboratory. One of the experimenters walked behind the user handling cables and preventing collisions.

2.2 Virtual Walking

Virtual walking requires participants to reproduce the physical head motions generated during actual walking but without physically locomoting. The changes in head position are fed to a neural network previously trained to recognize walking. The network discriminates when participants are walking-in-place from when they are doing anything else. When virtual walking is detected, they are moved forward in virtual space in the direction of head-facing. This appears to be intuitive; participants are able to navigate without being told they will move in the gaze direction. We used the same feed-forward neural network as the 1995 study (see [Slater, 1993] for details). Streaming position data to the neural network at 10 Hz gives good discrimination.

As with the 1995 study we used a neural network trained for *standard* virtual walking. This standard net was derived from the gait of the principal author. It has been effective in recognizing the walking-in-place motion. Casual visitors to the laboratory were able to replicate the movements; it was not necessary to train the system on the gaits of individual subjects.

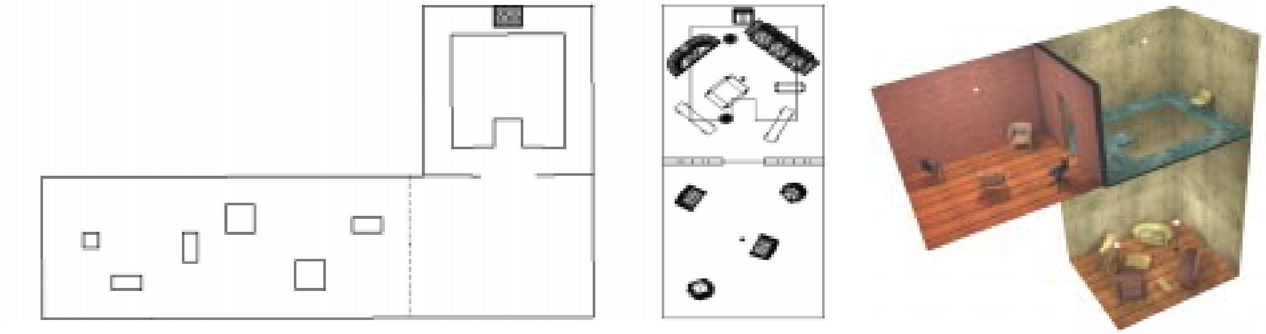
The neural network can make two types of errors. Type I is judging users to be walking when they are not; Type II is judging them to be not walking when in fact they are. The Type II errors typically occur on motion starting, Type I errors on cessation, and they manifest themselves as overshooting—sometimes causing virtual collisions. Type II errors are generally not so severe, since they manifest as momentary breaks in performance, giving a general slowness in locomotion. Type I error is more disturbing to users.

2.3 Flying

In the original experiment, flying was in the direction the hand pointed. This decoupled the head and hand so that subjects could freely look around while flying. However, subjects generally found it more difficult than flying in the direction of gaze. To make the flyer and virtual walker groups match, we chose locomotion along gaze (actually, head direction). A mismatch of movement along gaze direction can also occur when subjects look down at their virtual feet. Hence we forced the forward direction of the virtual feet to correspond to head direction.

2.4 The Virtual World and Scenario

The 1995 scenario consisted of a virtual corridor about 10 m long with an open doorway leading to another room. The corridor contained a number of boxes on the floor. Subjects could travel to a certain point along the corridor without being able to see through the doorway; instructions and training were given in this part of the scene (Figure 2a). This was mainly for acclimatization and for practice in locomotion and grasping of virtual objects.



(a) (b) (c)

Figure 2. (a) Original Slater environment, 1,000 polygons; (b, c) environment for current study, 40,000 polygons.

Figure 3. Sequence of images of the environment. The top left image shows a subject's view when entering the pit room. The top right shows the view when standing on the "diving board" on the ledge. The bottom images form stereo pairs of the view when looking down from beside the target chair (the left two images are for wall-eyed viewing; the right images are for cross-eyed viewing).

When a user enters the virtual room leading off the corridor, he or she is on a 0.7 m wide ledge 6 m above the floor of the room. The ledge goes all the way around the room and there is a chair on the ledge on the far side. The floor below is populated with living room furniture. A direct path from the doorway to the chair would mean walking out onto "empty space". However, it is possible to get to the chair "safely" by going along the edge of the room. This scene is inspired by Gibson's visual cliff experiment [Gibson, 1960] and fear-of-heights work by other researchers [Rothbaum, 1995].

Although we are using wide-area tracking, the virtual scene still must fit into a finite area. We therefore divided the tracked space into a training area and an experimental area, each of 5 x 4 meters. In virtual space these areas corresponded to a training room and the room containing the virtual pit. A virtual door prevents subjects from seeing the virtual pit room during training. We maintained the dimensions of the 1995 virtual pit room, and used a smaller virtual training area (Figures 2b, 2c).

A modern graphics engine (SGI Infinite Reality System) enabled us to use a much enhanced visual scene—about 40 times as many polygons (some 40,000 total), radiosity lighting, and texturing for almost half the polygons (Figure 3).

Because the 1995 study showed the importance of user association with the virtual body, we invested over 11,000 of the polygons in a detailed avatar (Figure 4). The subject was able to see his tracked virtual right hand connected by a virtual arm to his body. A subject looking down could see his virtual body and feet, and an untracked virtual left hand. The virtual body was oriented in the head direction. Consequently if one looked at one's virtual feet while swiveling the head, the virtual body shifted correspondingly. However, this effect was not always noticeable and only 10% of subjects reported it as a distraction.

2.5 MEASURES AND DATA COLLECTION

Several researchers have undertaken the quantification of presence [Slater, 1994; Ellis, 1996; Pausch, 1997]. Subjective reporting using questionnaires is the most common method. This method, however, relies on eliciting responses about subjects'

Figure 4. View showing avatar.

experiences *after* the event. Subjects must retain detailed memories of each part of the experience. An ideal measure would require recordings from subjects *while* immersed in the environment. A recent approach depends on gestalt psychology to record presence levels without interfering with the VE experience [Slater, 1998]. This relies on subjects indicating when they have a *break in presence* (BIP) from the virtual environment.

We retained the 1995 questionnaire-based method for determination of the virtual presence, but enlarged it substantially. The enlarged set of questions asks about various aspects of the virtual experience such as the sense of “being there”, frequency of dominance of the virtual world over the real one, sense of visiting versus viewing a scene, etc. These were interspersed with questions on the ease and effectiveness of locomotion and padded with filler questions. All presence and performance related questions were rated on a scale of 1-7; the total number of 6 and 7 scores was taken as the overall score. We augmented the questionnaire with an oral debriefing, inquiring into factors reinforcing the experience or causing BIPs. We encouraged free-form comments.

Both real and virtual views of sessions were videotaped. Debriefing sessions were audio taped. Tracking information and button-push events were recorded. Investigator observation of user foot motion and corresponding neural net judgments were recorded for virtual walkers, so as to yield goodness scores for the net.

3. THE EXPERIMENT

The experiments used a Silicon Graphics Onyx2 with one graphic pipe, two raster managers, four 195 MHz R10000 processors and 2 GB of main memory. The scene was rendered using OpenGL and locally developed software; the system maintained a frame rate of 30 Hz stereo. Viewing used a Virtual Research V8 head mounted display with true VGA resolution of (640x3) x 480 pixels per eye — 307,200 triads. This display consists of two 1.3 inch active matrix LCDs with a field of view of 60 degrees diagonal at 100% overlap and aspect ratio 4:3.

The input device was a joystick with four buttons; the experiment used two. The joystick and HMD were tracked by the ceiling tracker. The system had an overall latency of about 100 ms with a lag of about 500 ms for walking-in-place.

A total of 33 “naive” subjects participated in the study. The requirement was that they have no knowledge of the goals of the experiment. Each subject was paid $10. Naive subjects were grouped into flyers, virtual walkers, and real walkers, each with 6 men and 5 women. Another 11 subjects (10 men, 1 woman) were “expert” users who had experienced immersive virtual reality on several occasions and were generally working in the area of computer graphics. We included this group’s results in the analysis, and tested if expertise was a significant variable in the results. It was not.

The experiment consisted of a simulator sickness questionnaire with 16 categories [Kennedy *et al.*, 1993], the virtual experience, a repeat simulator sickness questionnaire, the presence questionnaire, and then an oral debriefing session. An investigator trained the subject in the training room, which had some chairs, a blue box, and a green box. Subjects practiced locomotion and picking up the blue box until they were comfortable with both. Boxes fell when dropped. Subjects were told to proceed with the experiment whenever they felt ready. The investigator did not speak again until they had completed the task. This task was to grasp the green box in the training room and carry it to the chair in the virtual pit room. Picking up the green box automatically opens the door between the two virtual rooms. Subjects were free to choose the path to the chair, either going along the ledge, left or right, or moving directly to the chair over the pit. Objectively we associate a path over the virtual pit with a lower sense of presence than one along the ledge.

4. ANALYSIS

To enable the comparison with the 1995 study an analysis was done using the original questions followed by one with our enhanced set. Another analysis was done on behaviors, observed and reported: consciousness of background noise, vertigo, actual path to the chair, willingness to walk out over the pit, etc.

We used the same binomial logistic regression analysis as was used in 1995 for presence, behavior, and locomotion responses [Cox, 1970]. We fitted a baseline model that uses only locomotion method as the independent variable. We then tested a number of other explanatory variables by starting from the baseline model and adding or deleting terms according to their significance level as judged against the Chi-squared distribution. We were most interested in degree of association with the virtual body, since in the 1995 study it was the dominant explanatory variable for extent of presence.

We present the questionnaire data, behavioral data, debriefing comments, and the details of the statistical analysis on the web page http://www.cs.unc.edu/~walk/walking_expt/.

5. RESULTS

5.1 Overall Conclusions

The experiment confirms the 1995 result that presence correlates highly with the degree of association with the virtual body. This seems to hold irrespective of anything else. The evidence suggests that presence is higher for virtual walkers than for flyers, and higher for real walkers than for virtual walkers. However, the difference between groups diminishes when oculomotor discomfort is taken into account. Oculomotor discomfort is one of the three diagnostic subscales measured by the simulator sickness questionnaire [Kennedy, 1993]. We found that it reduces presence for the virtual walkers and flyers, but does not do so for the real walkers. This likely has to do with the match between presence and proprioception—the greater match in the real walking case overcoming the disadvantages of discomfort. This result is very much in line with previous findings. Finally, if the goal is to have people assess locomotion as natural, easy, and uncomplicated, then real walking is better than the other methods.

5.2 User Reports

Subjective reports of the sense of “being there” were generally strong across all three groups. Although subjects were intellectually aware that they are in a simulation, the power of the human visual system triggers innate responses. One commented, “I was afraid to experience the falling sensation I might have had if I’d walked straight ahead [over the virtual pit].”

Subjects were also asked what factors, if any, broke them out of the simulation. Reports included incorrect behavior of the environment and avatar, background noise, and interference by the hardware. About 30% reported awareness of the cables as causing breaks-in-presence. About 15% of subjects commented on becoming more immersed in the experience once the investigator stopped giving instructions.

5.3 Locomotion

We found a strong significant difference between real walking and the other methods. Figure 5 illustrates mean responses to the three questions on locomotion.

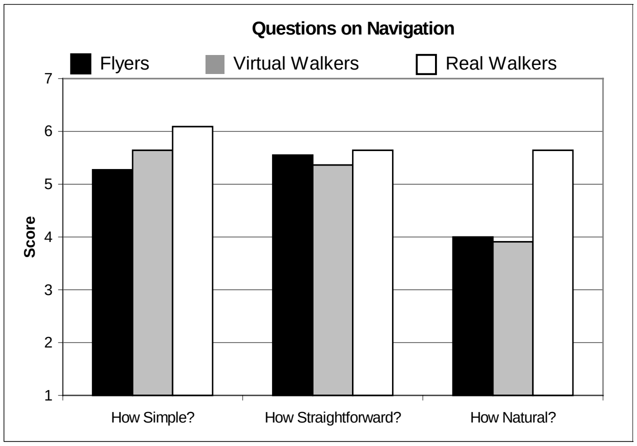


Figure 5: Ease of locomotion across groups.

Real walking associates with greater overall ease of locomotion as measured by the combination of the three locomotion questions. The overall model is not a good fit, and clearly other variables are needed to explain the variation among the subjects. No other variable in the experiment is significant. If each of the three questions about locomotion is considered separately, then the differences among the groups are not significant. This indicates that the three component results cluster together.

5.4 Behavioral Presence

By behavioral presence we mean the extent to which actual behaviors or internal states and perceptions indicated a sense of being in the situation depicted by the VE rather than being in the real world of the laboratory. A score was constructed from five components:

- A reported indicator of the extent to which the subject was aware of background sounds in the real laboratory (on a scale of 1 through 7);
- The extent to which their reaction when looking down over the pit was self-assessed as being similar to what it would have been in a similar situation in real life (on a scale of 1 through 7);
- The extent to which they had any vertigo or fear of falling when looking down over the virtual pit (on a scale of 1 to 7);
- Their willingness to walk out over the pit (on a 1 to 7 scale);
- The path they actually took to the chair on the other side of the pit – if they walked across the chasm the score was 0, if they went around the edge the score was 1.

This measure of behavioral presence correlates highly (and positively) with the subjective presence treated in the next section. Previous game playing is not significant, and otherwise an excellent fitted model depends on the same variables as that for subjective presence.

There is no significant difference in the impact of locomotion type on this behavioral presence score.

Oculomotor discomfort has a significant impact in conjunction with locomotion type. In particular, higher discomfort reduces behavioral presence for the flyers, but has no impact for the virtual or real walkers.

Association with the body contributes significantly to behavioral presence.

5.5 Subjective Presence

Using the original basic 1995 presence scoring method, we confirmed the principal results of that study:

- There were no significant differences at all between the groups (flyers; virtual walkers; and, in our study, real walkers).
- Association with the virtual body is positively associated with presence rating.

We also found that females had a higher sense of presence than males. However, since females also played computer games significantly less than males, substituting game playing for gender yields a better fitting model. Greater game playing is associated with lower presence. No other variables were significant.

Using the enhanced questionnaires, with four new questions added to the original three, produced richer results:

- There was a significant difference between flyers, virtual walkers and real walkers. However, the major significant difference was between the first group and the second two, with the virtual and real walkers reporting a significantly higher sense of presence than the flyers. If nothing else is taken into account, then the real walkers have a higher sense of presence than the virtual walkers.
- The higher the association with the virtual body, the greater the sense of presence, irrespective of other variables.
- Game playing is negatively associated with presence, irrespective of anything else. However, there is the same confounding of game playing and gender.

When oculomotor discomfort is brought into the model, then an interesting result occurs. There is then essentially no difference between real and virtual walkers, although these groups still have a significantly higher presence than for the flyers. However, there is a different impact of discomfort across the three groups. For the flyers and virtual walkers, higher discomfort is associated with decreased presence, whereas this is not the case for the real walkers.

6. UNEXPECTED RESULT — A COMPELLING VIRTUAL ENVIRONMENT EXPERIENCE

An unexpected by-product of this study was that real walking (and, to a lesser extent, virtual walking) through our enhanced version of Slater’s virtual environment yields a strikingly compelling virtual experience. “Wow!” “Whoa!” “Uh-oh!” are typical reactions of participants upon finding themselves at the open door to the ledge above the pit.

We have demonstrated the scenario to over 200 people. A few refuse to go through the door into the pit room at all. Others will make their way around the ledge to the chair, but refuse to come back. Many refuse to venture out over the pit. For those that do, it requires an obvious act of will, even after they have repeated the experience several times. As Gibson taught us, the visual cliff evokes deep instincts; violating it is a gut-wrenching experience. The total experience is substantially better than anything previously achieved in our laboratory; it sets a new standard.

We believe the compelling nature of the experience is due to the confluence of many factors:

- The visual cliff environment itself, the depth of the pit, the narrowness of the ledge
- Almost imperceptible end-to-end system lag, on the order of 100 ms
- Real walking about in a significant space
- The reasonably realistic avatar
- The visual fidelity of the detailed, textured, radiosity-lit scene
- The excellent resolution and color saturation of the V8 HMD
- The 30 Hz stereo frame rate achieved by the Onyx 2 Infinite Reality engine
- Stereopsis
- The precision and crispness of the tracker

It is quite beyond us to guess, much less measure, the contribution of each factor.

7. OBSERVATIONS, LESSONS, AND FUTURE WORK

Cables are without doubt the most unsatisfactory part of the VE experience. Some 30% of the subjects commented on this difficulty. We are working on wireless links.

Real walking is best for human-scale spaces, though not cheap.

Virtual walking seems clearly better than flying for exploring human-scale spaces, if one wants heightened presence or a visceral estimate of spatial extents. It is very inexpensive to implement.

Substantially improved virtual walking can be had. The present neural net implementation requires a somewhat exaggerated gait, which can distract participants. The lag on walking cessation creates fake virtual collisions and other BIPs. A miniaturized accelerometer on the head tracker is a promising alternate implementation. Results from early studies show Type I errors to be only 1%, Type II errors 11%; versus 3%, 32% for the neural net. We shall also investigate foot-floor contact sensing.

Avatar realism is worth a lot of work and investment, since user identification with the virtual body is such a strong factor in presence. In our experiment, the limp left hand and non-walking feet were disconcerting, but were not major BIPs. We are working on extending tracking to each hand and foot, and trusting inverse kinematics to do the rest of limb realism.

Clothing identification was surprisingly important to some subjects. We have experimented with video-fed image-based rendering to achieve visual realism for a viewer's own avatar. It is very promising.

Investigator location incongruity caused many BIPs, but fortunately they occurred only during training phases, not the experimental phases. Subjects reported that looking at the experimenter's voice location and seeing no one caused a BIP. We plan hereafter to have investigator instructions given only via the HMD headphones, and not localized. The headphones will also attenuate other incongruous laboratory noise.

Ambiguous and erroneous interpretations of questionnaire questions will not all be exorcised by pilot experiments. Questions require great care. Oral debriefing of subjects resolves many ambiguities.

8. ACKNOWLEDGMENTS

We thank the UNC Chapel Hill Tracker project for the wide-area tracker that enabled us to do this experiment. We also thank Phil Winston for tracker software support, Zac Kohn for accelerometer testing, Neil Golson for help with model creation, David Harrison and Kurtis Keller for hardware support, and Todd Gaul for video support.

This work was partially supported by NIH National Center for Research Resources number RR02170. Intel generously donated equipment used in this research. Anthony Steed is funded by the European ACTS project, COVEN (Collaborative Virtual Environments). Rui Bastos was funded by CNPq/Brazil, PRAXIS XXI, and SGI.

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