# Proprioception and Natural Walking in Navigation Metaphors for Virtual Environments

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## Introduction to VE and Presence

A Virtual Environment (VE) is a computer-generated setting in which a participant is presented with simulated conditions that can be controlled to varying degrees. These simulations serve several purposes, including research, entertainment, and training. VE technology has already been shown to have applications in immersion therapy for phobia patients (Harris, Kemmerling, and North, 2002), and may be a benefit in physical rehabilitation as well (Matsuoka, Allin, and Klatzky, 2002). Loomis, Blascovich, and Beall (1999) explore the use of VE technology for social psychology, as the control over VEs provides a solution to the difficulties in recreating real social interaction with a simulated audience. The primary benefit of using VEs in research is the degree of control over the environment that is afforded to the researchers. In theory, VEs should be able to bridge the gap between internal and external validity. While they can display an accurate representation of the real world, they are created and controlled by researchers, and so they effectively become a laboratory (Loomis et. al., 1999).

VEs can vary across several dimensions, including participant control over the field-of-view and orientation, the ability to manipulate objects in a scene, the ability to change location in a scene, and the degree to which the displays used are immersive. A VE display is said to be completely immersive if all input to a given sense originates from the virtual simulation. For example, a head-mounted display (HMD) is visually immersive because it blocks all visual input from outside the VE and presents the participant with a display that is entirely controlled by the VE. In addition to immersion, VEs are capable of providing the participant with a subjective feeling of “presence,” or the sensation of being in one place or environment, even when one is physically situated in another (Witmer and Singer, 1998). For VEs, the notion of presence refers to a displacement of a participant's self-perception from the real world to the computer-controlled environment (Draper, Kaber, and Usher, 1998).

*Virtual Environment Displays*

Often referred to as virtual reality (VR), most VEs are created using a combination of visual and auditory displays. There are two primary methods of presenting a virtual environment visually, each with benefits and shortcomings. A HMD-based virtual environment is created by placing a small screen in front of each eye. The screens are generally a part of a visor that is worn on the head resulting in a visual display that is completely immersive. One limitation of HMD technology is the narrow field-of-view that results from small screen size, making studies requiring cues from peripheral vision difficult. For example, Banton, Steve, Durgin, and Proffitt (2000) have shown that laminar flow (the perception of scene changes in the periphery of the field of view), which would be obscured with a small field-of-view, allows for more accurate calibration of locomotion, and thus HMDs would lead to poorer performance on these kinds of tasks. One potential solution to this problem is to use HMDs with a greater field-of-view, but such devices are often prohibitively expensive (some expanded field-of-view HMDs cost approximately $100,000). An alternative solution is to use a multi-screen visual display such as a CAVE (CAVE Automatic Virtual Environment) (Kenyon, 1995). Multi-screen visual displays present the participant with two or more large screens that comprise the participant's entire field-of-view and are visually immersive. Though HMDs benefit from being mobile, multi-screen displays provide the benefit of a full field-of-view as well as unrestricted head rotation while viewing the VE.

*Presence*

When using virtual environment technology, a participant can be presented either with an artificial virtual world, or with a virtual representation of a remote real world location. Immersion across multiple senses should not be confused with the creation of presence (Draper et. al., 1998). Presence that relates to the operation and manipulation of real world objects from remote locations is known as “telepresence.” Psychologically, the measurement of presence in these two VEs would be the same (Draper et. al., 1998) and thus we should be able to generalize an increase in presence in an artificial virtual environment to one simulating a real-world location.

A problem with presence (and an issue in the development of VE displays) is that the feeling of presence is highly subjective and therefore difficult to predict or measure. Witmer and Singer (1998) have developed a presence questionnaire for measuring both immersion and presence in virtual environments. This questionnaire includes questions on the interaction between sensory stimuli in the VE, environmental cues in the real world that may encourage involvement and interaction, as well as the individual participant’s likelihood of becoming personally involved in the simulated environment. An increase in the tendency to become personally involved in a virtual environment (which varies substantially among participants) was shown to have a positive association with subjective ratings of presence.

Given the effort to study and measure presence, it is not immediately obvious that increased presence in VEs is necessarily desirable. One reason that presence has been set as an ultimate goal in the design of virtual environment technology is the idea that increased presence leads to greater external validity in experiments based on VE technology (Loomis et. al., 1999). As presence increases in controlled VEs and as simulations begin to resemble real world environments, external validity in VE-based research would increase as well. In addition to improved validity, VEs allow researchers to safely place participants in environments which would be dangerous or unpleasant (Glicksohn and Avnon, 1997).

Recent studies have produced a substantial amount of support for the idea that presence leads to enhanced performance in VEs. In studies using the Witmer and Singer (1998) presence questionnaire, better performance scores on simple psychomotor tasks and tasks requiring spatial knowledge of a scene were associated with higher ratings on the questionnaire (i.e., a greater degree of presence).

Presence can be achieved in many ways and is influenced by factors that can be both internal and external to the VE. Prior to any modification of a VE display or simulation, a participant's subjective presence may be influenced by their own inclination to become involved in a VE. For participants using VE displays that are not completely immersive, Witmer and Singer (1998) argue that while presence in a VE does not require a full transition of one's attention from the physical environment to the VE, higher ratings of presence occur when a participant most sharply focuses his or her attention on the VE.

Presence can be enhanced by the possibility of interaction in a virtual environment (Regenbrecht and Schubert, 2002). In a study involving both real and imaginary opportunities for control in a VE, Regenbrecht and Schubert found a positive correlation between participants' estimation of control in a VE and presence. Furthermore, possible self-movement was shown to significantly increase spatial presence and realness of a VE, and simply the illusion of interaction significantly increased spatial presence, even in the absence of any actual interaction. As Held and Durlach (1992, p.111) commented, "telepresence will generally tend to increase with an increase in the extent to which the operator can identify his or her own body with the [simulated action]."

Thus, VE technology has applications in entertainment, education, and research. Though the use of this technology has the potential for revolutionizing psychological research, it often falls short because of limitations in both the technology and the understanding of factors that lead to its effective use. The relationship between presence and performance points to the need for VE designs that attempt to support further increases in the subjective feeling of presence.

## Proprioception in Virtual Environments

As mentioned in the previous section, the ability for a participant to control the VE plays an important role in the subjective rating of presence. A participant can potentially control a VE in three ways: manipulating objects in the VE, changing his or her location in the VE, and changing orientation in the VE. When using a multi-screen VE display, the participant often must remain in one place, the critical point at which the two or more screens comprise the entire field-of-view. Thus, any movement must occur through the use of a controller, although changes in orientation can, to a limited extent, be performed through natural head movements in a CAVE. For HMD-based VE displays, head and body movement is far less restricted. As stated earlier, control, or the illusion of control, significantly increases the degree of presence reported in a VE. Regardless of the visual display used in a given study, the problem remains that participants must be presented with a navigational device that will afford them such control. For movement in a VE, several factors influence the success of a given controller. In particular, it appears that both vision and proprioception play substantial roles in the support of subjective presence in virtual environments.

*Proprioception and Performance*

A study by Slater and Steed (2000) helps clarify the role of proprioception and body movement on the subjective report of presence in virtual environments. In their study, participants were given the task of walking through a virtual forest and were asked to take note of specific leaves on trees. Tree size varied such that participants were forced to look up and down or bend to see the special leaves, and this variation in size of tree allowed for a controlled measure of body movement through the virtual environment. There was a significant positive association between body and head movement and presence, suggesting that increased body movement results in a greater sense of presence.

Participants immersed in virtual environments are prone to disorientation and often have difficulty transferring spatial knowledge obtained in the VE to the real world (Grant and Magee, 1998). This may, to some extent, be a result of the frequent use of non-proprioceptive controls for navigation in virtual environments. In Grant and Magee's study, he compared a walking interface (proprioceptive feedback) to a joystick interface (non-proprioceptive feedback) in a navigational task that manipulated the training and testing environment. Participants were trained in either a real or virtual environment, and then tested in the same or different environment. This resulted in four training-testing pairs (Real-Real, Real-Virtual, Virtual-Real, Virtual-Virtual). The type of control (proprioceptive vs. non-proprioceptive) did not influence performance in a basic orientation task in the VE, but proprioceptive control was associated with improved performance in an object-finding task in real world testing. This suggests that using VE technology for navigation of areas that would typically be explored on foot, but are not readily available to be visited (e.g., battlefields, contaminated facilities, etc.), the use of controls with proprioceptive feedback would be beneficial.

In another study, Lathrop and Kaiser (2002) investigated the effect of proprioceptive and visual cues in an orientation task. Participants were asked to remember the relative location of two targets separated by a minimum of 120 degrees of visual angle that had been presented in either the real world, a desktop display, or HMD. When the targets were removed, participants were asked to point in the direction of one of these targets. It was found that participants demonstrated less deviation in pointing to the target object in the real-world and HMD conditions than the desktop display, despite the fact that equivalent visual information was presented in all three conditions. The data suggest that this was due to the effect of idiothetic information, defined as the spatial information about an environment generated as a function of body movements in space. This was available in HMD and real-world situations, but not in the desktop display condition. The Lathrop and Kaiser study further supports the idea that proprioceptive feedback improves subjective presence and task performance, and would be relevant to interface design for spatial search, navigation, and visualization tasks.

*Proprioception vs. Optic Flow*

Natural human geographical orientation relies on visual as well as proprioceptive feedback, but present navigation metaphors that are used to navigate in a VE generally omit proprioceptive feedback cues. Relationships have been found between presence and performance in tasks that provided either visual or proprioceptive feedback, but the question remains as to whether these factors are independent. An important question is whether these factors contribute separately to subjective ratings of presence. Bakker, Werkhoven, and Passenier (1999) examined the effects of proprioceptive feedback on navigation in a VE, varying the degree of proprioceptive feedback as well as the amount of optic flow (visual cues that indicate spatial orientation and movement). Results indicated that proprioceptive feedback provided the most reliable and accurate source of information for path integration, and that orientation based on optic flow alone was the most inaccurate and unreliable. Navigation metaphors, therefore, should take these benefits of proprioceptive feedback into account.

In another study, Kearns, Warren, Duchon, and Tarr (2002) examined the effect of proprioceptive feedback on presence and performance in a path integration homing task by manipulating the availability of visual and proprioceptive feedback cues. Four visual cue conditions were created by manipulating the availability of information about translational and rotational optic flow (texture on the floor and walls of the VE, respectively). Participants were presented with both optic flow cues, a single cue, or neither cue, in either a proprioceptive (motion-tracking walking system) or non-proprioceptive (joystick) control. For the joystick control, accuracy was the greatest when both optic flow cues were present and least when neither cue was present. When participants actively walk in these conditions instead of using a joystick, there ceases to be a significant association between optic flow cues and performance.  This would indicate that optic flow plays a less important role in a homing task when proprioceptive cues are present.

*Metaphors for Navigation in Virtual Environments*

As the role of proprioception in producing subjective presence seems to be important for certain kinds of tasks, the method in which proprioceptive feedback is provided should be examined.  There are several possible metaphors available for providing proprioceptive cues to the participant while navigating in a VE.  While some devices may be tailored to a specific task, such as the “virtual bike” (Pinho, Dias, Moreira, Khodjaoghlanian, Becker, and Duarte, 2002), the most common metaphor for navigation in VEs is one that is most analogous to natural walking.  The “Gaiter,” a new device that allows users to control locomotion through virtual environments by stepping in place, senses the movement of a person’s legs and treats this in-place walking as an indication of the user’s intent to move in a given direction (Templeman, Denbrook, and Silbert, 1999).  Since the control is tied to leg movement, the timing and extent of movement through the virtual environment reflects the pace set by the user.  A potential drawback of this device, however, is that while the pace of navigation is controlled by the participant, the actual act of walking in place contradicts the perceived movement forward perceived in the VE.

While the Gaiter requires a participant to remain in one place without the perception of forward movement, most linear treadmills are able to provide the same control over a participant’s location while providing proprioceptive cues for forward movement. Though linear treadmills provide the proprioceptive cues of forward movement, they suffer from a decreased ability to provide natural turning strategies in a VE. This limitation has been examined in a study by Vijayakar and Hollerback (2002), where turning strategies were observed in relation to performance on maneuvering ability using a linear treadmill. The study compared a rate control sidestepping strategy (turning rate was proportional to the distance the participant stood to either side of the center of the treadmill) to a torso-turning strategy (turning rate was proportional to the twisting of the torso), and judged performance as a measure of the number of collisions with obstacles in the VE as well as traversal time and traversal distance. The torso-turning strategy was found to provide more precise movement than the sidestepping strategy.

Eliminating the need for turning strategies altogether, a study by Iwata and Yoshida (1999) examined the results of performance on a path reproduction test using a “Torus Treadmill.” The Torus Treadmill, consisting of a looped set of perpendicular treadmills, provides two translational degrees of freedom to the participant, thus creating an infinite walking surface. This device is appropriate for navigation in VEs because, as Iwata and Yoshida comment, traveling on foot is an intuitive style of locomotion. Using the Torus Treadmill as the navigation device, participants were immersed in a VE that presented a grass-covered surface with several targets in the field of view. Participants were to travel to a target object, and then return to their original position, in a similar as the Kearns et. al. (2002) homing task. Performance using the Torus Treadmill was compared to performance using a joystick. Results indicated that the accuracy of path reproduction was greater for the Torus Treadmill than for the joystick.

The Gaiter, linear treadmill, and Torus Treadmill vary in three ways: 1) the extent to which movement in a VE using the device is analogous to the motion of human walking, 2) the ability for participants to orient themselves easily in environment, and 3) the number of degrees of translational freedom they afford. All three devices have been shown to provide superior performance over non-proprioceptive controls (i.e., joysticks, mouse and keyboard controls, etc.), especially in specific navigation tasks. However, there have been no studies directly comparing these different proprioceptive-control devices on performance with respect to each other. The proposed study is designed to determine the relationship between the resemblance of the controls to natural walking and performance in navigation tasks.

## An Experiment to Examine the Effectiveness of the Current Navigation Metaphor

### *Introduction*

Though increasing proprioceptive feedback has been shown to be associated with improved performance on navigation tasks (Grant and Magee, 1998), the factors that contribute to improved performance remain unknown. Does the addition of proprioceptive feedback to navigation devices solve the problem of low performance on navigation tasks in of itself, or is this increase in performance a result of the similarities of these navigation devices to natural walking?

In order to determine the nature of the effect of proprioception on performance in VEs, it is necessary to compare the current navigation devices used for producing proprioceptive feedback. Current navigation metaphors in VEs attempt to recreate a sense of similarity to natural walking, in which a participant is able to change his or her location and orientation in the virtual space as they would in the real world. The extent to which this similarity is achieved is limited by the design and the technology involved with each navigation device. Three devices in particular provide somewhat representative examples of controls based on a natural walking metaphor for navigation in virtual environments (See Table 1), and vary along two dimensions. The devices provide up to two degrees of translational freedom (each degree of translational freedom represents an axis along which the participant has proprioceptive motion cues) and either zero or one degree of rotational freedom. Natural walking, for example, does not present limitations when changing location and orientation, and thus consists of two degrees of translational freedom (forward/backward, and side to side), and one degree of rotational freedom. The "Gaiter" (Templeman et. al., 1999) is a gait-sensing device and has some similarities to natural walking. It is limited by its inability to provide participants with any proprioceptive translation cues. Because the Gaiter allows participants to turn in place, it provides one degree of rotational freedom. A linear treadmill, often used in navigation tasks for VEs (Grant and Magee, 1998), provides another example of a device based on a natural walking metaphor. In this case, the device provides one degree of translational freedom but zero degrees of rotational freedom. Instead of a proprioceptive rotation cue, turning is accomplished via torso-turning strategy (Vijayakar and Hollerback, 2002). Finally, a bi-directional treadmill, such as the Torus Treadmill (Iwata and Yoshida, 1999), provides two degrees of translational freedom as well as one degree of rotational freedom. With the differences between these three devices in mind, it would be possible to determine the extent to which similarity to natural walking enhances the effect of proprioception on performance in navigation tasks in VEs.

*Method*

The proposed study will compare these three devices to each other via a homing task (Kearns et. al., 2002), in which the participant navigates from an origin to two target points and then returns to the origin (accuracy is measured on the dimensions of distance traveled and angle turned when returning to the origin). A homing task is appropriate for this experiment, because it is a simple method of testing a participant's ability to accurately change location and orientation in a VE. As in the Kearns (2002) study, the two target points will be 425 cm and 225 cm from the origin point, respectively, and three paths will be produced by requiring a turn of 60, 90, or 120 degrees between the two targets. A mirror of these paths will be presented to make a total of six possible paths, decreasing the predictability for the participant.

The visual display for this study will be an immersive HMD. Participants will perform the homing task using the set of six paths. The order of the devices will be determined using a Latin square model to avoid fatigue and learning effects during the experiment. The study will employ a repeated measure design, with all participants using all three control devices. In order to judge a learning effect, there will be N trials for each device, where N is based on the number of trials during pilot testing that result in asymptotic inter-trial performance improvements. To gauge the effect of experience, the mean results of the first quarter of the trials will be compared to the mean results of the last quarter. The dependent measures of distance traveled and angle turned for the last leg of the paths provide a means for determining the differences in performance between the three devices. For each of the six paths, the two dimensions of average distance traveled and average angle turned will be compared across the three devices.

*Pilot Study*

The results of the proposed experiment will indicate whether there is an association between the similarity of a navigation device to natural walking and performance on navigation tasks. Before the experiment is run, however, it would be useful to examine the extent to which the act of walking in place (as in the gait-sensing device) and walking on a treadmill compare to natural walking. Do participants using these devices demonstrate similar performance when they are able to perform navigation tasks in the real world? An answer to this question would aid in forming a hypothesis for the proposed study, as well as indicate performance discrepancies between gait-sensing devices and treadmills.

*Method*

Ten students of Carnegie Mellon University (five male, five female) were chosen as a convenience sample. They were given a distance estimation task designed to maximize the differences between walking in place and using a treadmill (for our experiment, a standard automated linear treadmill was used) and to minimize performance differences that would result solely from different turning strategies between the two modes of travel. The task was designed to require a minimum of turning, and would have to be long enough to demonstrate any categorical differences between the two conditions. Thus, the task involved visualizing a straight path between two prominent campus buildings. The starting location for the task was the front of Warner Hall and the target location was the entrance to Doherty Hall, approximately 675 feet away.

Participants were asked to imagine themselves walking along the complete length of this path at a normal walking pace and to indicate when they reached the target destination. The task was performed twice, once while walking in place and once while walking on a treadmill. For the treadmill condition, participants were asked to adjust the speed of the treadmill's belt to a comfortable walking pace (this rate was recorded). The order of the tasks was counterbalanced to eliminate practice effects and order effects such as fatigue. The amount of time required for participants to complete the task was recorded via stopwatch, and the number of steps required to traverse the distance were counted during each trial.

*Results*

Distance traveled was estimated by multiplying the rate chosen in the treadmill condition by the time required to complete that condition. Using this number, a feet-per-step measure was obtained, allowing an estimation of distance traveled in the walking in place condition as well. In general, participants underestimated the time and number of steps required to traverse this distance in both conditions (See Table 2). Though the mean distance traveled was greater for the walking in place condition (mean = 310.1 ft, st.dev. = 142 ft) than for the treadmill condition (mean = 283.8 ft, st.dev. = 85.8 ft), both conditions typically demonstrated an underestimation of 40% or greater. However, the study failed to find a significant effect of movement condition on number of steps taken or time taken to complete the task. This suggests that these two modes of control may be equivalent in terms of estimating distance.

*Discussion*

The pilot study did not show a significant variation in number of steps between devices. A possible explanation for the lack of an observable association between movement condition and steps taken could be that regardless of the movement condition, participants imagined traveling along the path at a constant velocity. As a result, the amount of time required to complete the task in each condition would be similar. If this was the case, it would be an indication that similarity to natural walking may not be associated with improved performance in tasks that benefit from proprioceptive cues. If an equal velocity in VEs resulted from input into the gait-sensing device or treadmill, then it is possible that there would not be a difference in the estimation of distance between devices, and that differences in the proposed task could be attributed to differences in the availability of rotational degrees of freedom.

*Summary of Proposal*

The proposed experiment would assist in determining the effects of similarity to natural walking in navigation devices during navigation tasks in VEs and has implications for the importance of natural walking in navigation metaphors. While similarity to natural walking may influence performance in early trials, experience may reduce these effects. If this is shown, it would indicate that a similarity to natural walking would only influence the amount of time required to become comfortable with the device, and not the ability for participants to perform a task in a VE. Selection of a control device, then, could be guided by the nature or goals of the study or use of VEs. For example, in public entertainment venues, where participants have brief access to the

VE controls, devices requiring little or no training would be desirable. In contrast, for studies involving longer exposure to the VE controls, and for which cost is a factor, less expensive devices may suffice. Ultimately, the differences between devices that would be observed in this proposed study should help researchers choose an optimal device for a particular VE experience, circumstance, or application.

Table 1

Three navigation devices for virtual environments

| Device | Translation | Rotation | Comments |
|---|---|---|---|
| Gaiter | 0 Axes | 1 Axis | Feet move, Can turn to reorient |
| Linear Treadmill | 1 Axis | 0 Axes | Walk forward, Gaze/Torso turning |
| Torus Treadmill | 2 Axes | 1 Axis | Walk forward, Can turn to reorient |
| Natural walking | 2 Axes | 1 Axis | No mechanical limitations |

Table 2

Pilot Study Data

| | Treadmill | | | In-Place | |
|---|---|---|---|---|---|
| Participant | #Steps | Time (sec) | Rate (mph) | #Steps | Time (sec) |
| 1 | 111 | 75 | 2.6 | 135 | 106 |
| 2 | 130 | 85 | 2.6 | 144 | 100 |
| 3 | 139 | 87 | 2.3 | 135 | 85 |
| 4 | 245 | 170 | 2.0 | 325 | 238 |
| 5 | 120 | 75 | 2.2 | 130 | 100 |
| 6 | 86 | 62 | 2.1 | 95 | 60 |
| 7 | 104 | 61 | 3.0 | 99 | 72 |
| 8 | 95 | 64 | 2.2 | 75 | 60 |
| 9 | 140 | 75 | 2.6 | 178 | 105 |
| 10 | 117 | 75 | 2.2 | 93 | 65 |

## References

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

Banos, R.M., Botella, C., Perpina, C., Alcaniz, M., Lozano, J.A., Osma, J., Gallardo, M. (2001). Virtual reality treatment of flying phobia. (**DATE**) *IEEE Transactions on Information Technology in Biomedicine, 6*, 206-212.

Banton, T.A., Steve, J., Durgin, F.H., & Proffitt, D.R. (2000). The calibration of optic flow and treadmill speed during treadmill walking in a virtual environment. *Investigative Opthamology & Visual Science, 41*, S718.

Blascovich, J., Loomis, J., Beall, A.C., Swinth, K.R., Hoyt, C.L., & Bailenson, J.N. (2002). Immersive virtual environment technology as a methodological tool for social psychology. *Psychological Inquiry, 13*, 103-124.

Bystrom, K.E., Barfield, W., & Hendrix, C. (1999). A conceptual model of the sense of presence in virtual environments. *Presence – Teleoperators and Virtual Environments*, *8*, 241-244.

Christensen, R.R., Hollerbach, J.M., Xu, Y., & Meek, S.G. (2000). Inertial-Force Feedback for the Treadport Locomotion Interface. *Presence – Teleoperators and Virtual Environments*, *9*, 1-14.

Draper, J.V., Kaber, D.B., & Usher, J.M. (1998). Telepresence. *Human Factors, 40*, 354-375.

Glicksohn, J., & Avnon, M. (1997). Explorations in Virtual Reality: Absorption, Cognition and Altered State of Conscoiusness. *Imagination, Cognition and Personality, 17*, 141-151.

Grant, S.C., & Magee, L.E. (1998). Contributions of proprioception to navigation in virtual environments. *Human Factors, 40*, 489-497.

Harris, S.R., Kemmerling, R.L., North, M.M. (2002). Brief virtual reality therapy for public speaking anxiety. *Cyberpsychology & Behavior, 5*, 543-550.

Held, R.M., & Durlach, N.I. (1992). Telepresence. *Presence – Teleoperators and Virtual Environments, 1*, 109 – 112.

Iwata, H., & Yoshida, Y. (1999). Path reproduction tests using a Torus Treadmill. *Presence – Teleoperators and Virtual Environments, 8*, 587 - 597.

Kearns, M.J., Warren, W.H., Duchon, A.P., & Tarr, M.J. (2002). Path integration from optic flow and body senses in a homing task. *Perception, 31*, 349-374.

Kenyon, R.V. (1995). The CAVE™ Automatic Virtual Environment: Characteristics and Applications. *Human-Computer Interaction and Virtual Environments, NASA Conference Publication #3320*, 149-168.

Ko, H.S., & Cremer, J. (1996). VRLOCO: Real-time human locomotion from positional input streams. *Presence – Teleoperators and Virtual Environments, 5*, 367-380.

Lathrop, W.B., & Kaiser, M.K. (2002). Perceived orientation in physical and virtual environments: Changes in perceived orientation as a function of idiothetic information available. *Presence – Teleoperators and Virtual Environments*, *11*, 19-32.

Li., W.J., Chang, C.C., Hsu, K.Y., Kuo, M.D., & Way, D.L. (2001). A PC-based distributed multiple display virtual reality system. *Displays*, *22*, 177-181.

Loomis, J.M., Blascovich, J.J., & Beall, A.C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behavior Research Methods, Instruments, & Computers*, *31*, 557-564.

Matsuoka Y., Allin, S.J., & Klatzky, R.L. (2002). The tolerance for visual feedback distortions in a virtual environment. *Phsyiology & Behavior, 77*, 651-655.

Pinho, M.S., Dias, L.L., Moreira, C.G.A., Khodjaoghlanian, E.G., Becker, G.P., & Duarte, L.M. (2002). A user interface model for navigation in virtual environments. *Cyberpsychology & Behavior*, *5*, 443-449.

Regenbrecht, H., & Schubert, T. (2002). Real and illusory interactions enhance presence in virtual environments. *Presence – Teleoperators and Virtual Environments*, *11*, 425-434.

Ruddle, R.A., & Jones, D.M. (2001). Movement in cluttered virtual environments. *Presence – Teleoperators and Virtual Environments*, *10*, 511-524.

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence – Teleoperators and Virtual Environments*, *6*, 603-616.

Slater, M., Steed, A., McCarthy, J., & Maringelli, F. (1998). The influence of body movement on subjective presence in virtual environments. *Human Factors, 40*, 469-477.

Slater, M., & Steed, A. (2000). A virtual presence counter. *Presence – Teleoperators and Virtual Environments, 9*, 413-434.

Stanney, K.M., Kingdon, K.S., Graeber, D., & Kennedy, R.S. (2002). Human performance in immersive virtual environments: Effects of exposure duration, user control, and scene complexity. *Human Performance, 15*, 339-366.

Templeman, J.N., Denbrook, P.S., & Sibert, L.E. (1999). Virtual locomotion: Walking in place through virtual environments. *Presence – Teleoperators and Virtual Environments, 8*, 598-617.

Vijayakar, A., & Hollerbach, J. (2002). Effect of turning strategy on maneuvering ability using the treadport locomotion interface. *Presence – Teleoperators and Virtual Environments, 11*, 247-258.

Witmer, B.G., & Kline, P.B. (1998). Judging perceived and traversed distance in virtual environments. *Presence – Teleoperators and Virtual Environments, 7*, 144-167.

Witmer, B.G., & Singer, M.J. (1998). Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence – Teleoperators and Virtual Environments, 7*, 225-240.