

**VIRTUAL EQUIVALENCE:  
Matching Visual Scene and Treadmill Walking Speeds  
in Virtual Reality**

by

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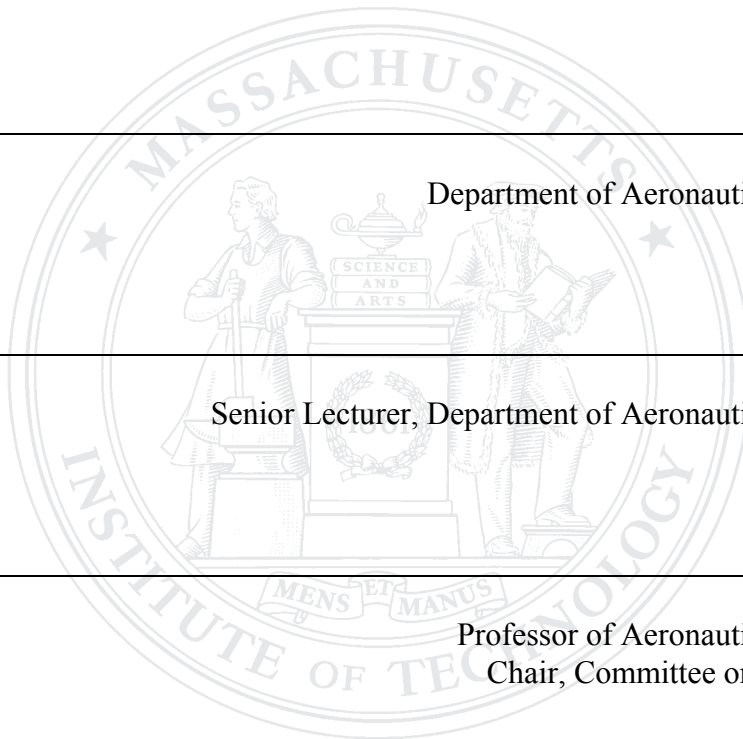
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## **ABSTRACT**

If we walk on a treadmill and are looking in the direction of motion of a moving virtual environment, the perceptions from our various senses are harmonious only if the visual scene is moving in a narrow range of speeds that are, typically, greater than our walking speed. This observation has been reported when we project a virtual environment through a display with a restricted field-of-view, such as a head-mounted display (HMD). When the subject feels that the scene-motion is natural for their walking speed, the ratio of the speed of his visual surround to that of the treadmill walking speed is defined as his perceptual equivalence ratio (PER) in that setting. Four experiments explored a set of conditions under which the PER measured on a treadmill is constant. The experiments, motivated by several hypotheses, investigated the relationship between PER and display type (HMD vs. either desktop monitor or on-screen projection), sense of presence in the virtual environment, and the magnitude of illusory self-motion (vection). We also investigated differences among subjects, and the stability of PER over time due to the limitations of working memory. Most experiments considered more than one hypothesis.

The first two experiments found that PER was affected by the type of display used, but found no correlation of PER with the sense of presence reported by the subject. A third experiment showed that PER was nearly the same whether we manipulated visual or treadmill speed (and asked the subject to match the other.) While PER values were often constant versus treadmill speed for any individual subject, they were very different from subject to subject. PER appears to be relatively stable over a short test session, but may be highly variable over extended periods of time. The last experiment showed that individual subjects PER values changed over time intervals as short as ten minutes, and revealed the importance of the subject's prior experience in PER experiments. This suggests that limitations of working memory may effect the repeatability of the PER measure. The definition and measure of PER for each subject may also provide a means for quantifying the magnitude of a clinical condition known as oscillopsia, where we perceive the world as non-stationary, such as moving independently of our head motions. These findings are important for a perceptually sensitive environment, such as virtual reality. Designers of virtual environments that utilize self-motion perception should consider calibrating PERs within a session for each individual user and be aware that that the subject's calibration may change over time.

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When the numbers acquire the significance of language,  
they acquire the power to do all things which language can do:  
to become fiction and drama and poetry.

—Bill James



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# 1 INTRODUCTION

In a perfect virtual reality environment, the perceptions accompanying our physical movements would match our expectations. If our simulations could do this reliably, then we would have achieved one of the fundamental goals of virtual reality – “to provide the user with a compelling sensation of an alternate environment (Harris et al., 2002).” There are, however, several limitations of virtual reality head-mounted display systems. These include a limited field of view, computational delays in updating the visual environment, optical distortions in the display hardware, lack of hardware calibration to the individual user, and inadequate corroborative sensory information. Virtual reality systems are routinely used in flight simulation, extravehicular activity training, military soldier training, and are widely used for research and entertainment. Spaceflight exercise equipment may one-day use virtual reality technology. For these and many other applications, it is important to understand how the limitations of virtual reality systems affect our perceptions while we are interacting with these computer-generated environments.

A large portion of recent virtual reality research has focused on increasing the illusory sense that one is moving in the virtual environment. This illusory sense of self-motion – “vection” (Fisher, 1930) – is one of the most important phenomena of virtual reality training and simulation. The onset of vection typically occurs when our central nervous system integrates the available sensory information and concludes that we are actually moving, when we are not. This sensory information may come from the visual, vestibular, somatosensory, proprioceptive, and auditory systems (Benson, 1990; Gibson, 1966; Howard, 1982; Johansson, 1977), all contributing to the same sense of self-motion.

If you are walking on a treadmill and the virtual environment is moving past you at the speed at which you are walking, the scene motion arguably should feel natural for your walking speed. It is hard to believe that it would not. Recent studies have shown, however, that in fact while walking on a treadmill and viewing a virtual environment, as projected in a head-mounted display that limits our field-of-view, it must move past you faster than you are walking if the

match between the scene motion and your walking speed is to be perceived as natural (Pelah et al., 2002; Banton et al., 2003). A similar result has been found for other kinds of motion, such as rotations and translations of the head while standing still (Jaekl et al., 2002). A state of perceptual equivalence has been reached when the motion of the visual surround matches that expected from the body's active movements. For the experiments discussed here, a dimensionless parameter was defined, the ratio of speed of the visual surround to that of the treadmill walking speed, called the perceptual equivalence ratio (PER). A PER value indicates how fast an individual sets the visual virtual environment to move past them to match their walking speed when they feel the match is "natural." PER may be defined for either linear or angular movements. In this thesis PER is considered in terms of linear motions. When viewing a virtual environment through a display that has a restricted field-of-view, such as in the Pelah et al. (2002) and Banton et al. (2003) studies, PER values are generally greater than 1.0 when the match of visual to bodily movement is perceived as natural.

It is important, for many applications, to provide an environment that will provoke the illusion of self-motion. These applications include extravehicular activity (EVA) training for spacewalking astronauts, aviation training and flight simulators, and even countermeasures to the physiological effects of spaceflight. Understanding the physiological mechanisms involved in perceiving self-motion is as important as creating the high-fidelity hardware that provides the sensory stimulation. The weightless environment of space provides a unique laboratory that allows us to isolate these physiological mechanisms. The linearvection studies (Oman et al., 2003) aboard the Neurolab space shuttle mission (which did not use a treadmill) were designed to seek these answers, and at the same time introduced new questions regarding self-motion perception: Why did the astronauts feel more "present" in the virtual environment in 0-G – beyond the fact that they reported greater linearvection magnitude reports? What is the functional role of corroborative sensory information on our perception of self-motion?

If there is a set of conditions in the virtual environment where we do not perceive the match of visual to bodily movement as natural, then it is possible for us to experience symptoms of oscillopsia. Oscillopsia is characterized by the major loss of perceptual stability of the surrounding environment (Bender, 1965), which is commonly experienced by patients with

vestibular disease. Head-movement contingent oscillopsia is commonly seen in astronauts returning from spaceflight. At this time, there are, unfortunately, no reliable means of quantifying oscillopsia. Current research efforts are aimed at developing novel methods for quantitative assessment of oscillopsia. Could PER be used to determine the magnitude of one's oscillopsia?

The aim of this study was to determine a set of conditions in which PER is constant for linear motions. Several experiments were designed to determine the boundaries of this constancy. The first and second addressed the question of whether visual scene motion seemed inappropriately slow for our walking speed if we use different types of displays that restrict our field-of-view. That is, we investigated the differences between display types (between a head-mounted display and a desktop monitor, or between a head-mounted display and an on-screen projection). We were interested in the different effects the displays might have on PER reports. This experiment also explored the constancy of PER over a range of treadmill speeds. The variability of individual's PER reports within- and between-sessions were also quantified. Previous experiments (e.g., Banton et al., 2003; Durgin and Kearns, 2002; Pelah et al., 2002) fixed the treadmill walking speed and manipulated the speed of the virtual environment until it matched their walking speed. If PER is truly a constant, then it should be independent of whether the visual or treadmill speed is manipulated. This was evaluated in the third experiment. The fourth, and final, experiment was designed to explore the stability of PER over time since we found the between-session variability was often quite large.

If our goal in these virtual environments is to match the speed of the virtual environment to our walking speed so that the self-motion seems natural, then it may be necessary calibrate the speed of the visual environment to each subject that uses a virtual reality simulation (that restricts our field-of-view but involves self-motion), particularly when that simulation involves walking on a treadmill. In the recent era, the virtual environments used for training and simulations are often replicas of the real world. It may not be practical to alter the objects in the virtual environment to increase motion parallax and the perceived speed of self-motion. Therefore, increasing the speed of the virtual environment may be the simplest solution for perceptual equivalence. The work described here should help in the design and calibration of virtual reality environments to

individual users, and to put limitations on the calibration values. With a set of conditions where PER is constant, we may be able to achieve a high level of fidelity in virtual reality with a display of limited field-of-view.



## 2 BACKGROUND

### 2.1 Perception of True Speed

There has been surprisingly little research that quantifies our perceived speed of self-motion while walking in a virtual environment with objects of known size, rather than one with an abstract scene. Traditionally, a moving dot or stripe pattern is used to elicit a sense of self-motion. Without information about the actual size of the objects in the moving scene, it is impossible to estimate our true linear speed. If this is the case, then our speed estimations will be relative and only time-to-contact can be judged. In everyday walking or running we generally do not get direct feedback on our true speed unless we happen to spend extensive periods of time on a motorized treadmill with a digital speed display. Ecologically, we have been “calibrated” to estimate our speed based on visual flow at normal eye heights (Warren and Whang, 1987).

Consider a vertically oriented stripe pattern that is moved horizontally. Our perceived self-velocity increases linearly with both angular speed and spatial frequency of the stripes (Diener et al., 1976). It has also been shown that increases in edge rate and/or the global optic flow have additive effects on velocity judgments (Larish and Flach, 1990). Edge rate is the frequency with which local discontinuities cross a fixed point of reference in the observer’s field of view (Warren, 1982). Global optic flow, on the other hand, is the motion of objects in the world scaled in altitude units (such as eye heights per second) (Warren, 1982). In practical terms, the further you are from a moving object, the slower it appears to move. Therefore, the closer you are to a moving scene, the faster you think you are (or the scene is) moving.

If we considervection in a virtual environment, our perception of speed is different depending on the type of projection used – monoscopic or stereoscopic. Palmisano (2002) found that stereoscopic cues increased our perception of speed and of self-displacement duringvection in depth – but only when these cues were consistent with monocularly available information about self-motion. That is, these stereoscopic cues did not increasevection by making the environment seem more three-dimensional, but provided extra binocular information relating to the perceived speed.

There appear to be differences between the two regions of our visual field (i.e., central and peripheral) in estimating linear speed of objects. Brooks and Mather (2000) measured the perceived speed of motion in depth for an object in our central and peripheral visual field, and found an apparent reduction of speed in the periphery (relative to the central visual field). This may indicate that the spatial sensitivity to object motion of the visual system changes with eccentricity. If there is one point in the visual field where speed information is encoded veridically, then there is a gradient of mis-information across the rest of the visual field (Johnston and Wright, 1986).

It has long been asserted that the periphery is the most important region of our field-of-view for self-motion detection. Recent experiments have shown that linear vection does not depend on stimulus eccentricity, but rather the stimulus size and speed (Nakamura, 2001). At first glance, this seems to be in conflict with the Brooks and Mather (2000) finding. There is, however, one fundamental difference between the two studies: object motion (Brooks and Mather, 2000) vs. self-motion (Nakamura, 2001). We must also remember that without information related to the actual size of the moving objects, it is difficult for us to estimate the true speed of vection.

In a study where the horizontal field-of-view was progressively increased from 37° to 180° (i.e., it did not restrict the field-of-view to either central or peripheral), the perceived velocity of self-motion increased 13% over the field-of-view range (van Veen et al., 1998). In the recent era, virtual reality systems that limit the use of our peripheral field-of-view have become an integral part of research involving self-motion perception. As a result of this widespread use of narrow field-of-view displays that often project to our central visual field, the limitations in speed perception of this region of our field-of-view may become more apparent.

## **2.2 Visual perceptions during active movements**

For many of us, as we move our head, we take for granted that what we see is the result of our head moving and that the world around us is, and remains, stationary. This is not the case for everyone. Patients with a vestibular disease may be unable to see clearly while moving, a condition resulting in clinical symptoms termed oscillopsia (Bender, 1965).

In virtual reality, it is often presumed that the system is properly calibrated if the visual image motions correspond exactly to our physical movements. This assumption may be inaccurate. It seems hard to believe that we would need the virtual visual world to move by an amount more (or less) than our physical movements in order for that motion to feel natural. This would constitute a “perceptual mismatch.” Three experiments that exhibit this phenomenon – and conflicting findings – are discussed below.

### **2.2.1 “Perceptual Stability During Head Movements in Virtual Reality” (Jaekl et al., 2002)**

In one study (Jaekl et al., 2002), subjects wore a Virtual Research V8 head mounted display (60° diagonal field-of-view) operating in monoscopic mode. The subject’s head was at the center of a two-meter diameter sphere that was textured with a red and white checkerboard pattern. Their aim was to investigate the tolerance to discrepancies between head motions and the resulting visual display as a mechanical tracker updated that display. Subjects made sinusoidal head-movements (both rotational and translational in separate experiments) and adjusted the gain of the visual display until the image was judged to be stable relative to the external world. In these experiments, therefore, both linear- and angular-PER measures are meaningful. Typically, for the display to be judged stable, subjects set the visual world gain so that it moves in the direction opposite to the head movement by an amount greater than the head movement itself. That is, both linear- and angular-PER were, on average, between 1.1 and 1.8. The authors cited the underestimation of the perceived distance to the display, particularly in the cases of translational head movements as a possible explanation for PER values greater than 1.0.

### **2.2.2 “Perception of Walking Speed” (Banton et al., 2003)**

Engineering intuition would tell us that if we matched the speed of the virtual environment to that of the treadmill, then our perceptions of self-motion in that environment would seem natural. However, Banton et al. (2003) found that this match does not feel natural unless that environment is moving faster than we are walking

Subjects walked on a motor driven treadmill while wearing an n-Vision Datavisor (52° diagonal field-of-view) head mounted display operating in monoscopic mode. As with all head-mounted

displays, the limited field-of-view eliminated the optic flow we typically get in our peripheral visual field. The subject's task was to look in the direction of motion and adjust the speed of the virtual environment ("scene speed") (in 0.5 mph increments) until it appeared to match their walking speed. On average, they matched the fixed treadmill speed of 3 mph with a scene speed of approximately 4.6 mph. In terms of PER, the average was roughly 1.5.

The experiment tested two other conditions: looking down towards the ground and looking towards the side, both while walking on the treadmill and wearing the same head-mounted display. In either condition, the subjects adjusted the scene speed to correspond to the fixed treadmill speed of 3mph. The subjects were fairly accurate at matching the scene speed to their walking speed (PER values close to 1.0). Banton et al. (2003) explained these findings in terms of radial and lamellar optic flow. While looking forward in the virtual environment, the scene motion is predominantly radial flow. The image motion when looking down at the ground in front of you or to your side is primarily lamellar which, they suggest, is necessary for us to perceive our walking speed accurately.

The findings reported by Banton et al. (2003) seem to be in conflict with those presented by Jaekl et al. (2002). If Jaekl et al. (2002) were to interpret his results in terms of radial and lamellar optic flow, then based on the Banton et al. (2003) result the PER-like measures they reported should be close to 1.0 for head rotations (yaw, pitch, and roll) – but the measures were, in fact, greater than 1.0. There are several differences between the two studies, namely the vestibular stimulation (Jaekl: sinusoidal accelerations, Banton: approximately constant velocity) and the visual image (Jaekl: checkerboard sphere with squares of unknown size, Banton: structured highway scene with objects of known size). The findings between the two studies are only in agreement when comparing fore-aft linear head movements (Jaekl et al., 2002) with that of Banton et al. (2003) when the subjects were looking in the direction of motion while walking on the treadmill. Here, the PER values were, on average, greater than 1.0.

### **2.2.3 “Calibration of Optic Flow produced by Walking” (Durgin and Kearns, 2002)**

Durgin and Kearns (2002) recently reported that if the virtual environment contains enough objects to support motion parallax, then we can accurately match the speed of the virtual environment to our walking speed, whatever the type of optic flow. In their experiment they used two “richly-textured corridors.” One of the corridors had randomly positioned textured pillars (providing inter-object parallax and salient cues about time-to-passage), and the other did not. There was no mention of the type of texturing in the corridors, spatial frequency of the pillars, nor of the type and field-of-view of the head-mounted display used. They found that PER values did not differ reliably from 1.0 with pillars in the corridor, and even in the absence of pillars, PER values rose only about 10%. Durgin and Kearns (2002) argue that our calibration (between scene speed and walking) in virtual reality can be quite good if the environment is “sufficiently rich” with objects and textured images close to the axis of motion.

As mentioned above, Durgin and Kearns (2002) used a corridor virtual environment, whereas Banton et al. (2003) used large open highway. Both virtual environments had objects of known size and realistically textured objects. Even though the scene used by Banton et al. (2003) was “sufficiently rich” with objects, the PER values were greater than those observed by Durgin and Kearns (2002). If Banton et al. (2003) included additional objects close to the subject’s viewpoint, conceivably they may have seen PER values closer to those reported by Durgin and Kearns (2002).

### **2.3 Treadmill versus Over-Ground Walking**

As mentioned earlier, when we walk on a treadmill and simultaneously view a virtual environment that is projected by a device with a limited field-of-view (such as a head-mounted display), we need that environment to move faster than we are walking for the motion to feel natural. It could also be argued that is a result of changes in walking induced by using the treadmill itself (reviewed below). If, however, treadmill walking was significantly different from over-ground walking, we would be hesitant in using these popular exercise devices as a substitute for over-ground walking or running.

A few subtle differences between treadmill and floor walking have been noted, mainly in the realm of kinematics, electromyographic (EMG) patterns, and heart rate measurements (Murray, 1985). When walking on a treadmill, subjects tended to marginally decrease their stride length and increase their stride frequency as compared to over-ground walking at the same speed. A significant increase in EMG activity, particularly in the quadriceps, and a slight increase in heart rate also accompanied this treadmill walking. These increases could be artifacts due to apprehension about stumbling or falling on the treadmill. Murray (1985) concludes that, in general, the kinematics of or the EMG patterns accompanying treadmill walking were not significantly different from those of floor walking.

## **2.4 Presence**

The advancement of computer technology has made it possible to easily create virtual environments with very intricate models, photo-realistic textures, and even animated objects. These virtual environments can replicate the real world in great detail, and, perhaps, significantly increase our sense of being present within that environment. This sense of presence, or “being there,” is popularly defined as “the subjective experience of being in one place or environment, even when one is physically situated in another (Witmer and Singer, 1998).” Presence, a very complicated percept, is affected by many factors and can be measured in a variety of ways (see Lombard and Ditton, 1997; Ijsselstein et al, 2000).

All else being equal, the sense of presence in the virtual environment should increase with the number of sensory systems stimulated. Usoh (1999) compared the experiences in an immersive virtual environment between three locomotion modes: walking, walking-in-place, and flying. Subjects wore a Virtual Research V8 head mounted display that was tracked by a ceiling tracker. The walking condition allowed subjects to walk freely around the entire virtual scene as though they were in a real environment. Walking-in-place is a bit misleading, as this required the subject to reproduce physical head motions generated during walking, but without physically locomoting. Last, flying was purely passive motion through the environment. Presence was measured via a seven-question post-trial survey. Real walking and walking-in-place gave a greater sense of presence than flying, but the contrast between real walking and walking-in-place was not significant.

## **2.5 A Model for Working Memory**

The most widely accepted model of working memory is that defined by Baddeley (1995), which is comprised of three core components: a verbal component, a spatial component, and a central executive. The verbal component, which represents information in linguistic form, includes the phonological store and articulatory loop. Analog, or visual information is included in the spatial component. The interface between the verbal and spatial components is defined as the central executive. The central executive also controls the switching of attention between the verbal and spatial components.

The spatial component, called the “visuo-spatial sketchpad,” often represents information in the form of visual images (Baddeley, 1995; Logie, 1995). Since the visuo-spatial sketchpad also represents spatial orientation (in addition to analog, or visual) information, it likely combines visual information with that received from the body’s orientation receptors (i.e., motor output, haptic, tactile, and perhaps vestibular cues). Some researchers (Smyth and Pendleton, 1990; Woodin and Heil, 1996) suggest that models of working memory should include a motor output related-, or kinesthetic-component.

If we believe that there is this separate kinesthetic component of the working memory model, then it is likely no different from other forms of working memory – subject to analogous limitations on duration and capacity. The length of time that items are kept in working memory is shortened if they cannot be rehearsed. In a task that requires the verbal working memory, recall accuracy decays exponentially with time if intervening tasks prevent this rehearsal (Melton, 1963). The more items you are asked to remember, the faster the decay. In addition, verbal working memory is also limited by the amount of information it can hold – typically 7 +/- 2 items (Miller, 1956). Recently, it has been suggested that the number of items presented be limited to five, and as few as three for maximum effectiveness (Doumont, 2002). Experiments investigating the mechanisms involved in the disruption of motor memories have traditionally kept the number of motor tasks to three (Shea and Titzer, 1993). In studies related to kinesthetic memory, there has been no mention of either the time constants of decay or of the number of physical, or bodily, movements that can be kept in working memory (Laabs, 1973; Podbros et al., 1981; Smyth and Pendleton, 1990; Woodin and Heil, 1996; Smyth and Waller, 1998). This

may result, in part, from the tasks used to study kinesthetic memory, which often rely on immediate performance. This immediate performance might also significantly diminish (or even exclude) any dependence on memory, particularly for visuo-kinesthetic tasks (Podbros et al., 1981).

The repeatability of selected tests for basic motor skills (e.g., balance, orientation, sense of rhythm, kinesthetic precision, and flexibility) has recently come into question (Rinne et al., 2001). There was a significant difference in performance on the tandem forward walking and on the balance bar between test- and retest-sessions separated in time by one week. The authors suggest that participants may discover different techniques after several trials, and that motor learning may have influenced the retest session. The authors do not cite the limitations of short-term working memory as a cause for the change in performance between sessions, though arguably it could have played a role.

When the subjects are matching visual- and treadmill-walking speeds (“matching speeds”), they must rely on the visuo-spatial and kinesthetic components of working memory. The question to ask, which appears to not have been answered so far, is: How long does the memory of the matching speeds last? If our memory of the matching speeds for perceptual equivalence decay over time, or we change the techniques used between sessions when matching speeds, then the PER measure will likely change. Several experiments in this thesis addressed this question.



### 3 HYPOTHESES

The aim of this study was to determine a set of conditions in which linear PER is constant. The experiments were driven by several hypotheses. These hypotheses included the effects on PER of display type, the sense of presence in the virtual environment, the magnitude of vection, differences among subjects, and the stability of PER over time due to the limitations of short-term working memory. Most experiments considered more than one hypothesis.

It was hypothesized that for motion along the gaze axis, a display with a relatively smaller field-of-view will be characterized by larger PER reports. A smaller field-of-view should lead to the subject setting the scene speed much faster than they are walking (and faster than a larger field-of-view display) probably due to underestimating the magnitude of the optic flow produced by that moving scene. That is, when comparing a head-mounted display (48°H x 36°V physical field-of-view) with either a desktop monitor (24°H x 18°V), or an on-screen projection (48°H x 36°V) the reported PER should be similar between the head-mounted display and on-screen projection, but relatively larger for the smaller desktop monitor.

The sense of presence, or “being there,” was hypothesized to be greater when wearing a head-mounted display than when viewing a monitor or with an on-screen projection. The greater presence when wearing the head-mounted display is believed to result from the relatively larger field-of-view. Additionally, the sense of enclosure within the virtual environment provided by the head-mounted display’s shroud should provide an increased sense of presence when the field-of-view is held constant. PER values are expected to also depend on the assumed eye height of the subject and size of objects in the virtual environment. A related question we wanted to ask was: Is there a relationship between PER and the sense of presence?

Both Jaekl et al. (2002) and Banton et al. (2003) presented data for an entire subject population and reported that large ranges of motions are judged correct for corresponding physical motions. It was hypothesized that each individual subject shows a narrower range of responses than that of the entire population. In other words, the difference in average PER between subjects is large compared to the variance of PER measured within any individual subject.

The repeatability (or stability) of PER over time or repeated trials is an important related question. If our perceptions are not repeatable, then over time, we may have a range of responses more consistent with that of the population. This leads to the question of whether PER is a perceptual “state” or “trait” of an individual. If PER is a trait, then it should be constant over time. If, however, it is a state, then the underlying mechanisms governing the instability of PER over time must be investigated. It was hypothesized that PER relies on working memory. Our memory of stimuli degrades, the cues we attend to, or the strategies we use change over time and this causes variability in PER between experimental sessions. The direction of change in PER with time, if any, cannot be predicted a priori since short-term working memory is believed to mediate the changes in PER between these experimental sessions. That is, subjects tend to forget the scene speed that matched their treadmill walking speed or the reporting strategies they used in the previous session and therefore may not reproduce that match reliably.

In prior experiments by Pelah et al. (2002) and Banton et al. (2003), when measuring PER, the treadmill speed was held constant and the subjects adjusted the speed the virtual environment moved past them (“scene speed”) until it felt natural for their walking speed. If PER is consistent, it should be possible to allow the subject to have control over either the treadmill or the scene speed. If, under both paradigms, they produce the same PER, then it can be said that PER is relatively constant, at least within a session.

Non-constant PER values, particularly over the range of treadmill walking speeds, may be correlated with how fast one thinks they are moving. If this was the case, we wanted to ask : Is there a correlation between PER and vection magnitude? If there is a correlation, does a greater PER lead to a greater vection magnitude report?

Answering these questions will, in part, aid in quantifying the importance of virtual environment properties (object scaling, pictorial realism, etc.) and their effects on our perceptions during active movements in virtual reality. These experiments also help to define the precision of our perceptions (within a session), and to determine how these perceptions might change over time. With this knowledge we will have better insights into the modeling and calibration of virtual environments.

## 4 METHODS

### 4.1 Experiment 1: Head-Mounted Display (HMD) versus Desktop Monitor (LCD)

#### 4.1.1 Participants

Six subjects from the MIT community, three male and three female, completed the experiment. No subjects failed to complete the experiment because of motion sickness symptoms, discomfort caused by wearing the experimental equipment, or fatigue resulting from walking on the treadmill. Their ages ranged between 21 and 25 years. All subjects volunteered and none had previously viewed the experimental stimulus. None possessed prior knowledge of the goals of the experiment, or expected results. No subjects had previously taken part in an experiment where PER was the dependent measure. All subjects were in good health, free from visible gait abnormalities, had normal or corrected-to-normal vision, and had prior experience with a motor driven treadmill. Each subject completed the experiment in approximately one hour.

#### 4.1.2 Equipment and Materials

Virtual Research manufactured the V8 head-mounted display (HMD). The head-mounted display accepted a 640 x 480 pixel, 60 Hz signal (standard VGA). The field of view was 60° diagonal (48°H x 36°V) with 100% binocular overlap. Head tracking was not used. The 17" flat panel digital liquid crystal display (LCD) monitor, manufactured by Dell, supported 32-bit true color and also accepted a 640 x 480 pixel, 60 Hz signal. From the subject's perspective standing on the treadmill, the field-of-view of the image displayed on the monitor (24°H x 18°V) was approximately half that of the virtual image in the head-mounted display.

The graphics were rendered using Vizard v2.10 (WorldViz, Inc.), an OpenGL-based architecture that utilizes the scripting language Python to rapidly build interactive virtual worlds. A Pentium 4 Xeon 2.4 GHz computer displayed the graphics and handled the data collection during the experiment. A single NVIDIA Quadro4 XGL graphics card with a stereo sync connector and 128MB memory output separate VGA signals to the left and right eyes of the head-mounted display for stereoscopic projection. Once the head-mounted display was donned, the subjects adjusted the inter-pupillary distance until the projected image was fused. The frame rate was typically greater than 30 frames/second.

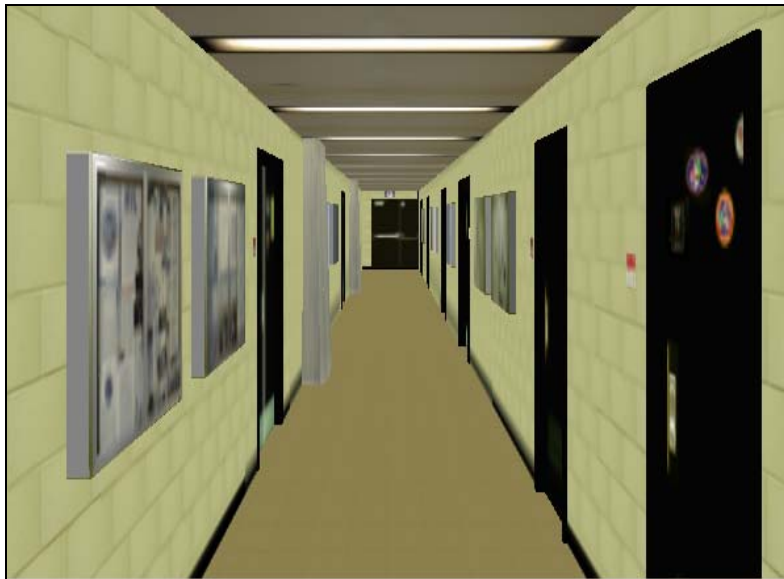
All experimental trials used a motor driven treadmill (Trotter CXTplus). The treadmill had a useful speed range of 1.0 – 8.0 mph in 0.1 mph increments. Subjects wore their own shoes, comfortable for walking. In the event of an emergency, the treadmill could be easily stopped, and would come to rest in approximately two seconds.

All data was recorded from the subjects using a standard USB gamepad. The buttons on the gamepad were used to toggle between onscreen instructions and to adjust the display speed. The gamepad, in conjunction with Vizard v2.12, wrote the dependent measures to an ASCII data file at the scene frame rate (typically 30 Hz).

During each experimental trial, the subject viewed a three-dimensional rendering of a virtual environment in the head-mounted display while walking on a motorized treadmill. The virtual environment was a replica of the Man-Vehicle Laboratory (MVL) hallway on the first floor of Building 37 at the Massachusetts Institute of Technology (MIT). A replica of a real, and familiar, hallway was used to provide scaling information with objects of known size. 3D Studio Max v5.0 (Discreet, Inc.) was used to create all of the models. The surface textures are digital photographs of the actual hallway surfaces. The cross-sectional dimensions of the real and virtual hallway are 2.0 meters wide by 2.5 meters high. The virtual hallway was extended by replication to give the impression of an infinite corridor. Figure 1 and Figure 2 compare the real and virtual MVL hallways. (There was no door at the end of the hallway in the virtual environment actually seen by the subject. The subject could not see the door at the end of the hallway, but saw a black dot due to the appearance of an infinite corridor. Figure 2 has a door at the end of the virtual hallway to show the similarity with Figure 1.) The viewpoint in the virtual environment was adjusted for each subject individually to match his or her actual eye height. A subject walking on the treadmill while wearing the head-mounted display is shown in Figure 3.



**Figure 1. Real MVL Hallway**



**Figure 2. Virtual MVL Hallway**



**Figure 3. Subject on Treadmill**

#### **4.1.3 Experimental Design and Procedure**

Before starting the experiment, each subject was introduced to the experiment instructions – “adjust the speed at which the hallway moves past you such that it feels natural for your walking speed.” The experimenter emphasized that subjective perceptions should drive the reporting rather than attempting to match numerically the scene speed with the treadmill walking speed. (Some subjects understood that this task had a “correct” answer and were constantly questioning the accuracy of their scene speed setting.) The subjects were also familiarized with the treadmill (and the range of test speeds), the head-mounted display (and the various fit adjustments), and the USB gamepad (affixed to the front display panel on the treadmill). The pertinent buttons on the gamepad were texture coded to aid in locating and identifying them when exterior vision was occluded by the head-mounted display. The subject mounted the treadmill and donned the head-mounted display. Once on the treadmill, the experimenter guided the subject’s one hand to the gamepad, and the other to the treadmill handrail. From this point on, all instructions were

displayed in the head-mounted display and were supplemented by verbal coaching when necessary.

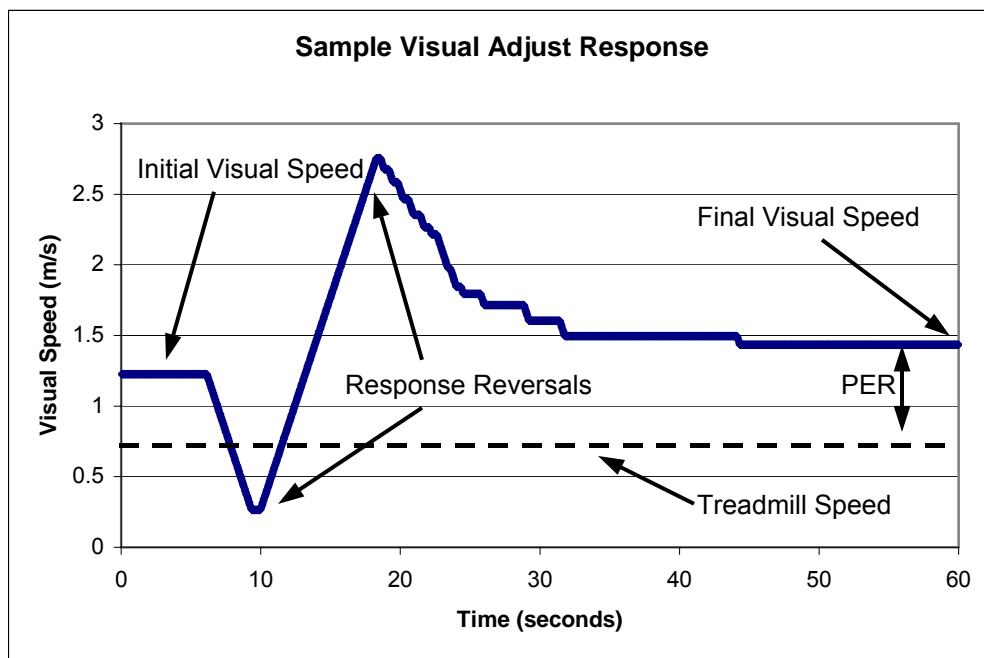
The 24 experimental trials were divided equally among the two display conditions (head-mounted display or desktop monitor), the three treadmill speeds (0.5, 0.7, 1.0 m/s), and the initial x-axis “looming” speed of the hallway (25 or 175% numerically of the treadmill speed). There were two repetitions at each condition. The treadmill speeds were in blocks of four repetitions, whereas the initial x-axis “looming” speeds were varied pseudo-randomly (Table 1). The division of the experimental trials by display and treadmill speed allowed for scheduled breaks during which the experimenter had the opportunity to ask questions relating to strategies and/or perceptions. The subjects were also encouraged to describe the strategies they used, their perceptions in the virtual environment, and comment on their overall experience during these scheduled breaks.

**Table 1. Head-Mounted Display versus Desktop Monitor Experimental Design**

Display	Trial	Treadmill Speed (m/s)	Initial Visual Speed (m/s)	Display	Trial	Treadmill Speed (m/s)	Initial Visual Speed (m/s)
HMD	1	0.5	0.125	Monitor	13	0.5	0.125
HMD	2	0.5	0.875	Monitor	14	0.5	0.875
HMD	3	0.5	0.875	Monitor	15	0.5	0.875
HMD	4	0.5	0.125	Monitor	16	0.5	0.125
HMD	5	1.0	0.25	Monitor	17	1.0	0.25
HMD	6	1.0	1.75	Monitor	18	1.0	1.75
HMD	7	1.0	0.25	Monitor	19	1.0	0.25
HMD	8	1.0	1.75	Monitor	20	1.0	1.75
HMD	9	0.7	1.225	Monitor	21	0.7	1.225
HMD	10	0.7	0.175	Monitor	22	0.7	0.175
HMD	11	0.7	0.175	Monitor	23	0.7	0.175
HMD	12	0.7	1.225	Monitor	24	0.7	1.225

Each trial began with the subject walking at the prescribed treadmill speed. After the subject depressed the gamepad “toggle” button, the virtual hallway was displayed translating at a constant velocity (25 or 175% numerically of the treadmill velocity). When the hallway first appeared, the subject was instructed to determine if the hallway was moving too fast or too slow for their walking speed. They used two additional buttons on the gamepad to adjust the scene speed so that it matched their walking speed. The subject had integral control over the scene speed. Their final scene speed setting was obtained after two response reversals were completed

– a type of method of limits protocol (similar to that used by Banton et al., 2003). For example, if they first indicated that the scene speed was too slow for their walking speed they would increase the scene speed until it was too fast, then decrease until too slow, and then set the scene speed until it matched their walking speed (vice versa if they first indicated that the scene speed was too fast). Each trial lasted 60 seconds. The steady state scene speed at the end of the trial was taken as the subjects’ matching scene speed. Sample data is shown in Figure 4. It depicts the response reversals and the relationship between the visual speed set by the subject and the fixed treadmill speed as a function of time.



**Figure 4. Sample Response Plot, Adjusting the Visual Speed to Match a Fixed Treadmill Speed**

At the end of each trial, the subjects were asked to give a subjective estimate of their greatest sense of presence during the last trial. They rated their sense of “being there” in the virtual environment on an analog scale that ranged from “not there” to “completely there.” Using this rating scale assumes that the sense of presence can be measured on a continuum (e.g., Freeman et al., 2000; Ijsselstein et al, 2001). (Presence may also be classified as a discrete “here versus there” phenomenon (Slater and Steed, 2000). In this thesis we treat presence as a continuous metric.) After reporting their sense of presence, they depressed the toggle button to advance to the next trial.



During all portions of the experiment, the experimenter observed each subject closely to prevent inadvertent falls, changed the treadmill speeds, provided assistance if motion sickness symptoms were to arise, and answered questions.

#### **4.1.4 Dependent Measures**

During each trial the computer automatically wrote the scene speed and the corresponding timestamp (in trial time – 0 to 60 seconds) to a data file. After each trial ended, no further additions were made to the data file. The final scene speed could be determined from this data file. In addition to the final scene speed, PER was calculated – the ratio of the scene speed to the treadmill speed. More importantly, the time course of hallway speed adjustments (made by the subjects) could be observed to determine if the subjects were following the instructions correctly. The subject's answer to the post-trial presence question was recorded to a separate data file.

All statistical analyses were performed using Systat v10 (Systat, Inc.) and StatXact v5 (Cytel Software Corporation). All statistically significant results reported are to  $p < 0.05$ , unless otherwise stated.

## **4.2 Experiment 2: Head-Mounted Display (HMD) versus On-Screen Projection (VREX)**

### **4.2.1 Participants**

Seven subjects from the MIT community, four male and three female, completed the experiment. No subjects failed to complete the experiment because of motion sickness symptoms, discomfort caused by wearing the experimental equipment, or fatigue from walking on the treadmill. Their ages ranged between 21 and 27 years. All subjects volunteered. Four had participated in the head-mounted display versus desktop monitor experiment (Experiment 1). Approximately three months separated Experiments 1 and 2. None possessed prior knowledge of the goals of the experiment, or expected results. All subjects were in good health, free from visible gait abnormalities, had normal or corrected-to-normal vision, and had experience with a motor driven treadmill. Each subject completed the experiment in approximately one hour.

### **4.2.2 Equipment and Materials**

The same equipment and materials was used as in the head-mounted display versus desktop monitor experiment, with one exception: an on-screen projection (48°H x 36°V field-of-view) replaced the liquid crystal display monitor. The projector, manufactured by VRex, Inc., supports 16.7 million colors and also accepted a 640 x 480 pixel, 60 Hz signal. The projection screen was placed in front of the subject, and the projected imaged, displayed monoscopically, matched the field-of-view of the head mounted display (both horizontally and vertically).

### **4.2.3 Experimental Design and Procedure**

Same as the head-mounted display versus desktop monitor experiment.

### **4.2.4 Dependent Measures**

Same as the head-mounted display versus desktop monitor experiment.

### **4.3 Experiment 3: Visual and Treadmill Speed Matching for Perceptual Equivalence**

#### **4.3.1 Participants**

Seven subjects from the MIT community, four male and three female, completed the experiment. No subjects failed to complete the experiment because of motion sickness symptoms, discomfort caused by wearing the experimental equipment, or fatigue from walking on the treadmill. Their ages ranged between 21 and 27 years. All subjects volunteered. None possessed prior knowledge of the goals of the experiment, or expected results. All subjects were in good health, free from visible gait abnormalities, had normal or corrected-to-normal vision, and had experience with a motor driven treadmill. None had participated in the head-mounted display versus desktop monitor experiment (Experiment 1) or the head-mounted display versus on-screen projection experiment (Experiment 2). Each subject completed the experiment in approximately thirty minutes.

#### **4.3.2 Equipment and Materials**

The same equipment and materials was used as in the head-mounted display versus desktop monitor experiment. Subjects wore the head-mounted display in all trials.

#### **4.3.3 Experimental Design and Procedure**

The same type of method of limits protocol was used to set the matching visual or treadmill speed (as in Experiments 1 and 2). Each subject was instructed to “adjust the speed at which the hallway moves past you (or the speed at which you are walking on the treadmill) so that you perceive (1) the visual scene speed as natural for your walking speed, and (2) hallway appears stationary relative to the unseen world beyond.” Each trial lasted for 60 seconds, which gave the subjects enough time to perform the response reversals and make the required adjustments to their speed settings.

The 12 experimental trials were divided equally among the two adjustment method conditions (visual or treadmill), the three treadmill speeds (0.62, 0.89, 1.25 m/s), and the speed of the independent variable (either visual or treadmill speed). If, for example, the treadmill speed were fixed, the initial visual speed would be either 0.22 m/s (0.5 mph) faster or slower, numerically, than the treadmill speed. Similarly, if the visual speed were fixed, the initial treadmill speed

would be either 0.22 m/s faster or slower than the ideal treadmill speed. There were two repetitions at each condition.

The design allowed for the exploration of two related questions – Is PER dependent on the variable being adjusted (visual or treadmill speed)? Over what time interval does PER repeat (with intervening trials)? The following table (Table 2) details the experiment design. There are two adjustment methods: in the visual method, V(T) is the visual speed set by the subject to match a fixed treadmill speed (T) presented to him. In the second (treadmill) method, T(V(T)) is the treadmill speed set by the subject to match a fixed visual speed, V(T) which was previously determined.

**Table 2. Visual and Treadmill Speed Matching for Perceptual Equivalence Experimental Design**

Trial	Conditions	Scene_V (m/s)	Tread_V (mph)	Vection
1	V(T2)		2.0	<i>Modulus</i>
2	T(V(T2))			
3	V(T1)		1.4	
4	V(T3)		2.8	
5	T(V(T1))			
6	V(T2)		2.0	
7	T(V(T3))			
8	V(T1)		1.4	
9	T(V(T2))			
10	T(V(T3))			
11	V(T3)		2.8	
12	T(V(T1))			

In the preceding table, the ovals indicate values recorded from the subject. The treadmill speeds from lowest to highest are T1, T2, and T3. The arrows show that the recorded scene speed at the first V(T2) trial was then used as the fixed scene speed in the T(V(T2)) trials, and similarly at the other treadmill speeds. Therefore, if the variable being adjusted (scene or treadmill speed) had no significant effect on PER,  $T(V(T)) = T$ . For example, if  $V(T2) = 1.5$  where  $T2 = 2.0$ , then if the variable being adjusted had no effect,  $T(1.5) = 2.0$ .

#### **4.3.4 Dependent Measures**

There were three measures recorded during each trial. These measures included the speed the visual environment moved past the subject (either set by the subject or held constant) and the treadmill speed (again, either set by the subject or held constant). From the visual and treadmill speeds, a PER was calculated. The third measure was the self-reported magnitude of self-motion (vection). Vection was reported on a magnitude estimation scale that set the vection perceived at the first trial (labeled the “modulus”) at the value ‘10.’ All subsequent vection reports were compared to this modulus. For example, if the subject felt he was moving twice as fast as the modulus he would report ‘20’; half as fast, ‘5.’

## **4.4 Experiment 4: The Effect of Working Memory on PER**

### **4.4.1 Participants**

Ten subjects from the MIT community, six male and two female, completed the experiment. No subjects failed to complete the experiment because of motion sickness symptoms, discomfort caused by wearing the experimental equipment, or fatigue from walking on the treadmill. Their ages ranged between 21 and 27 years. All subjects volunteered. None possessed prior knowledge of the goals of the experiment, or expected results. Five subjects had taken part in one or more of the earlier experiments (Experiment 1, 2, or 3) several months prior. All subjects were in good health, free from visible gait abnormalities, had normal or corrected-to-normal vision, and had experience with a motor driven treadmill. Each subject completed the experiment in approximately ninety minutes.

### **4.4.2 Equipment and Materials**

The same equipment and materials was used as in the head-mounted display versus desktop monitor experiment. Subjects wore the head-mounted display in all trials.

### **4.4.3 Experimental Method**

The same modified method of limits scene speed adjustment protocol was used in this experiment as Experiment 1. The 12 experimental trials were divided equally among six “phases” separated in time (Table 3). Only one treadmill speed was used ( $0.98 \text{ m/s} = 2.2 \text{ mph}$ ). There were two repetitions in each phase. The initial visual speed was either 0.76 (Rep 1) or 1.2 m/s (Rep 2). During the time in-between phases, subjects typically worked on their computer or “surfed the web.” They were not allowed to walk up and down the actual hallway to compare their perceptions with those in the experiment, or encouraged to develop new reporting strategies.

**Table 3. Working Memory Experimental Design**

Trial	Phase	Time (min.)	Rep
1	1	0	1
2	1	0	2
3	2	10	1
4	2	10	2
5	3	30	1
6	3	30	2
7	4	40	1
8	4	40	2
9	5	80	1
10	5	80	2
11	6	90	1
12	6	90	2

#### **4.4.4 Dependent Measures**

There was only one dependent measure in this experiment: the final scene speed set by the subject.

## 5 RESULTS

Four experiments are discussed in this section. The subjects were consistently asked to adjust the scene speed so that it felt natural for their walking speed, or the converse, to adjust the treadmill speed so that it felt natural for the projected visual image motion.

### 5.1 Experiment 1: Head Mounted Display (HMD) versus Desktop Monitor (LCD)

The experimental method section mentions that the initial x-axis “looming” speed of the hallway was either 25% or 175% of the treadmill walking speed. The required response reversals were designed to minimize, if not eliminate, any potential effect of this initial scene speed on the scene speed set by the subject or on their sense of presence. Therefore, this independent variable was not included as a factor in the repeated measures analysis.

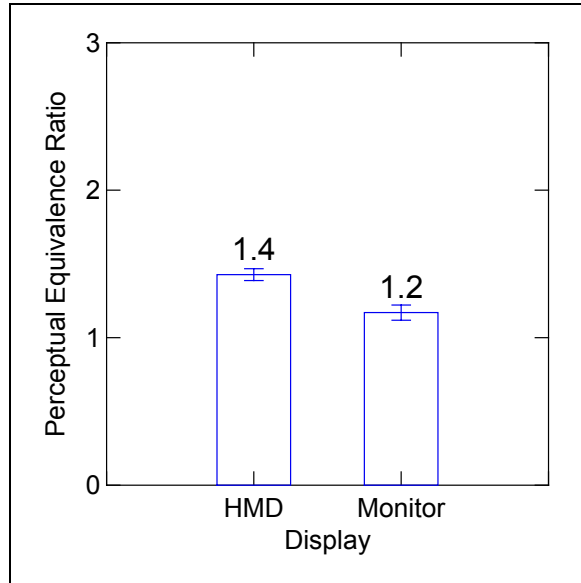
#### 5.1.1 Perceptual Equivalence Ratio (PER)

For each PER measure, the data set was structured as a three factor repeated measures analysis across Display (2 levels), Treadmill Speed (3 levels), and Repetition (4 levels). Each participant repeated each stimulus condition four times. The repeated measures data was analyzed using a General Linear Model (Systat v10).

##### 5.1.1.1 Head Mounted Display (HMD) versus Desktop Monitor (LCD)

The desktop monitor gave a slightly lower PER rating than the head mounted display ( $F(1,5) = 6.547$ ;  $p = 0.051$ ) (Figure 5). This marginal trend is in the direction opposite of that hypothesized. Not all participants exhibited it. Two of the six subjects did not show any marked difference in PER between the two displays.

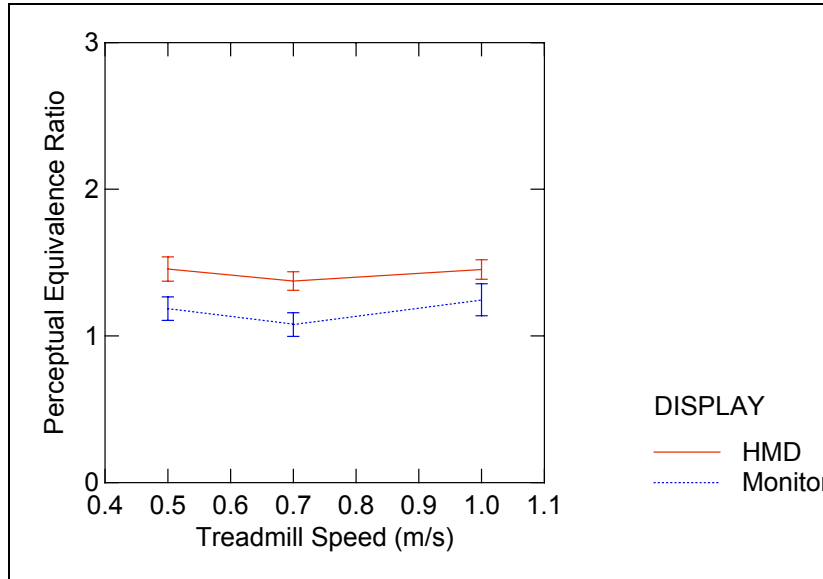




**Figure 5. Experiment 1: PER (Mean  $\pm$  SEM), Head-Mounted Display (HMD) vs. Desktop Monitor (Monitor)**

#### **5.1.1.2 Treadmill Speed**

The data showed no significant effect of treadmill speed on PER. PER was nearly invariant within the range of the treadmill speeds examined in this experiment (Figure 6). A linear regression of PER vs. treadmill speed showed the slope of the trend was not significantly different from zero for either display.



**Figure 6. Experiment 1: PER vs. Treadmill Speed (Mean ± SEM)**

### 5.1.1.3 Between- and Within-Subject Differences

The differences in average PER between subjects were large compared to the variances of PER measured within any individual subject (Figure 7 and Figure 8). While wearing the head-mounted display, the variance in PER for an individual subject was typically half of the population variance due to the differences in mean responses of individual subjects. Subject variances in PER on the desktop monitor were smaller than the head-mounted display (for four of the six subjects). The other two subjects had variances that were nearly the same as the population variance (Figure 9).

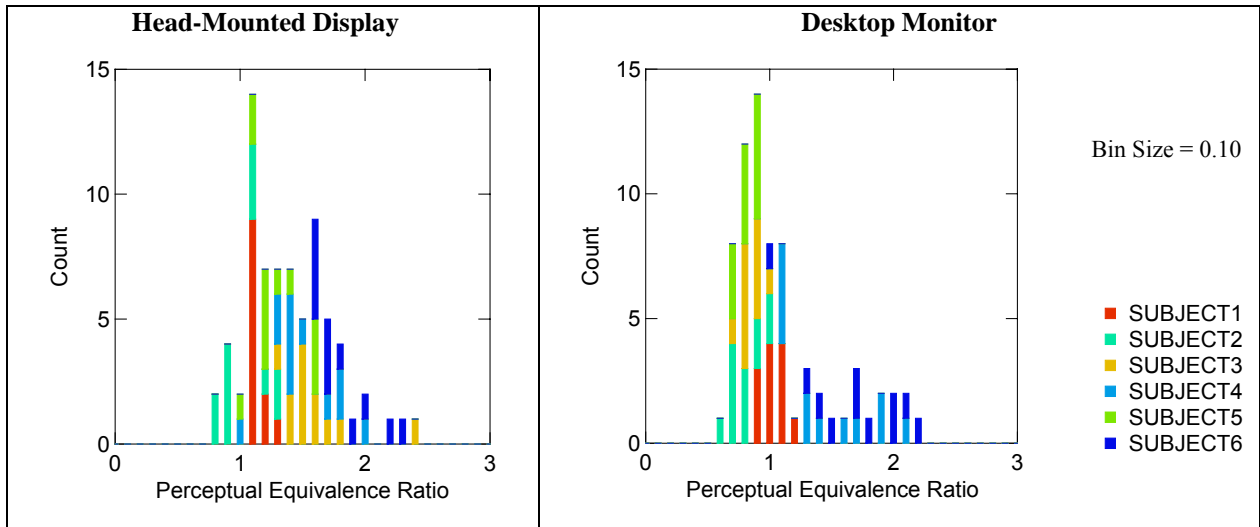


Figure 7. Experiment 1: PER Histograms, Head-Mounted Display (Left) and Desktop Monitor (Right)

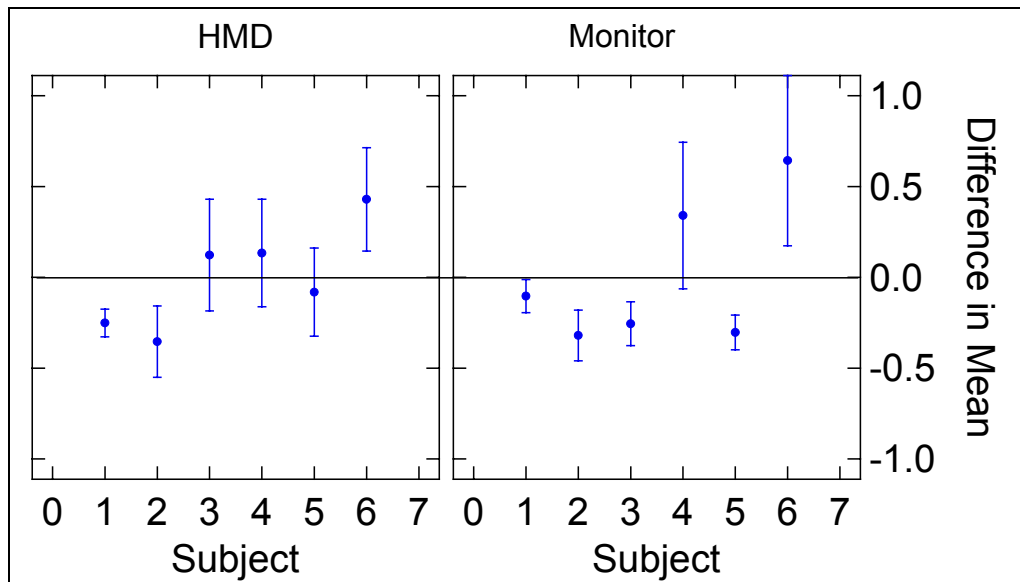


Figure 8. Experiment 1: Average PER by Display (Mean  $\pm$  SD), Each Subject compared to the Overall Average

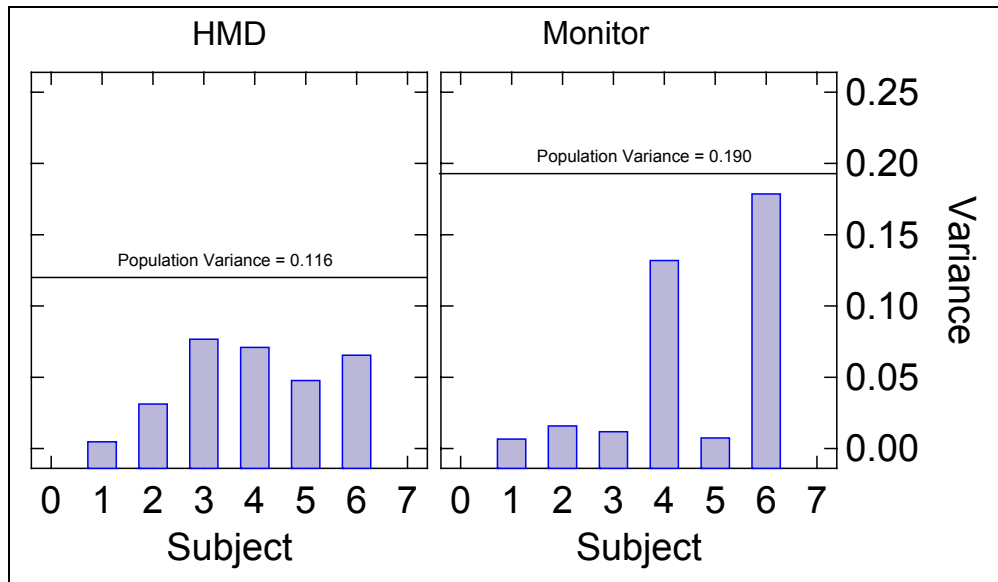


Figure 9. Experiment 1: Variance in PER, Each Subject compared to the Overall Variance

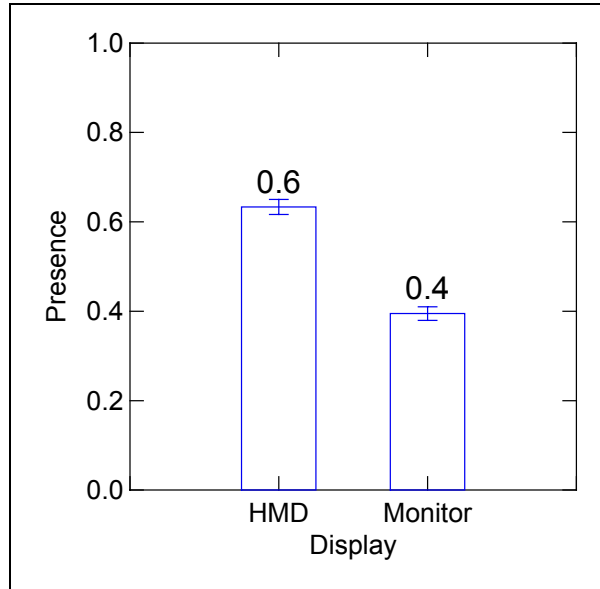
### 5.1.2 Presence

At the end of each trial, the participants rated their sense of presence on an analog scale anchored at one end by 0 (“not at all there”) and the other end at 100 (“completely there”) – a scale commonly used by presence researchers (Freeman, 2000; Ijsselsteijn, 2001).

As with PER, the presence data was structured as a three factor repeated measures analysis across Display (2 levels), Treadmill Speed (3 levels), and Repetition (4 levels). The repeated measures data was analyzed using a General Linear Model (Systat v10).

#### 5.1.2.1 Head Mounted Display (HMD) versus Desktop Monitor (LCD)

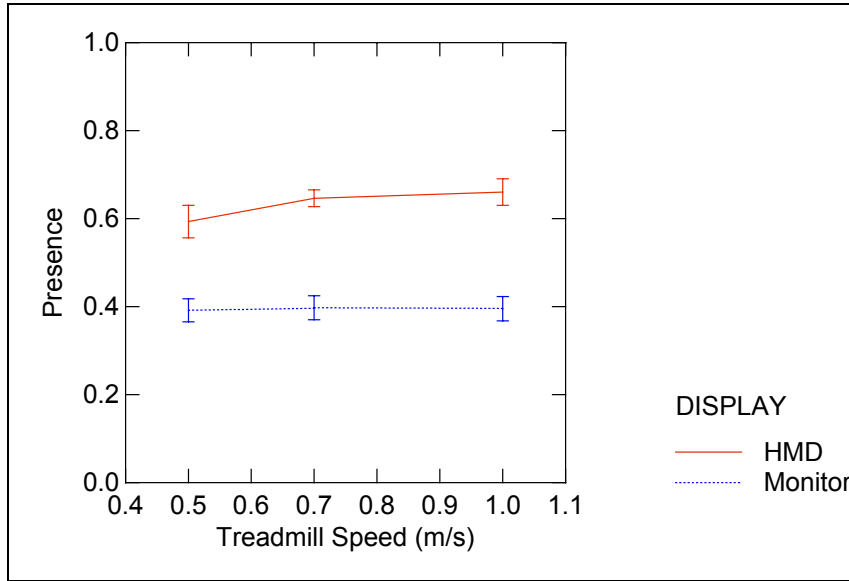
When the subjects wore the head-mounted display their presence reports were significantly greater than when they viewed the desktop monitor ( $F(1, 5) = 9.899$ ;  $p = 0.025$ ) (Figure 10). The direction of this difference was as predicted (for five of the six subjects).



**Figure 10. Experiment 1: Presence (Mean  $\pm$  SEM), Head-Mounted Display (HMD) vs. Desktop Monitor (Monitor)**

#### **5.1.2.2 Treadmill Speed**

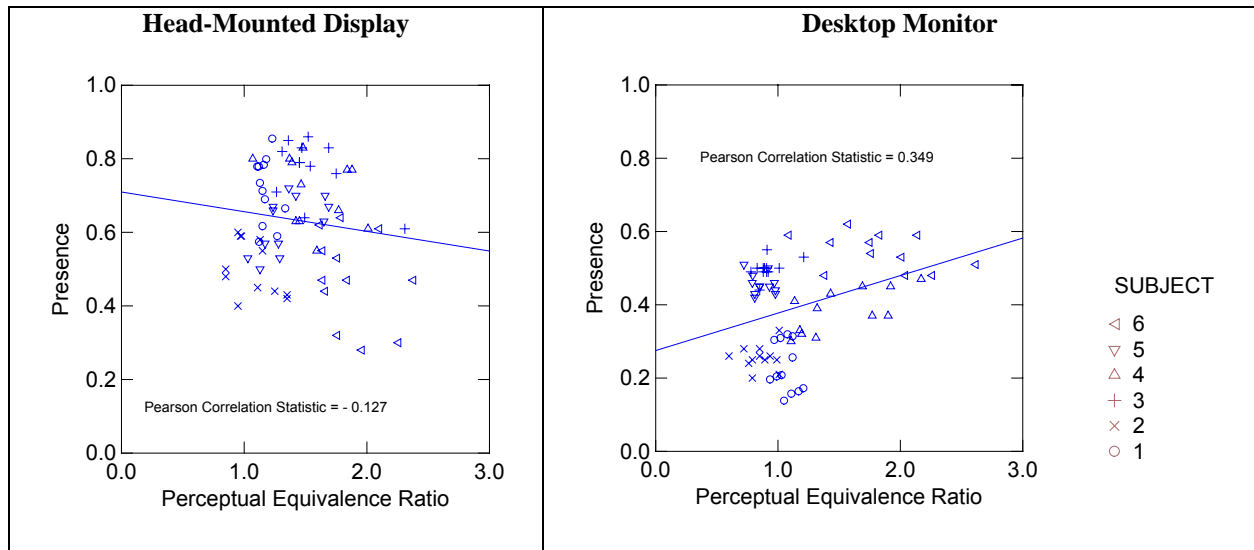
As for the PER measure, the data showed no significant effect of the treadmill walking speed on the subjective report of presence (Figure 11). For the head-mounted display, there appeared to be a slight increasing trend in presence treadmill speed increases. A linear regression found that the slope of the presence versus treadmill speed trend was not significantly different from zero, for either the head-mounted display or the desktop monitor. This suggests that presence is relatively constant across the range of treadmill speeds tested.



**Figure 11. Experiment 1: Presence vs. Treadmill Speed (Mean ± SEM)**

### 5.1.3 Correlation between PER and Presence

A linear regression found no significant trend in PER against presence when the subjects were wearing the head-mounted display (Figure 12). Presence was significantly correlated with PER when viewing the desktop monitor (slope = 1.19 ± 0.38; p = 0.003). This correlation, however, was not supported by subsequent experiments.



**Figure 12. Correlation between PER and Presence, Head-Mounted Display and Desktop Monitor**

## 5.2 Experiment 2: Head Mounted Display (HMD) versus On-Screen Projection (VREX)

### 5.2.1 Perceptual Equivalence Ratio (PER)

The data set was structured as the same three-factor repeated-measures analysis as before: Display (2 levels), Treadmill Speed (3 levels), and Repetition (4 levels). It was analyzed using a General Linear Model (Systat v10).

#### 5.2.1.1 Head Mounted Display (HMD) versus On-Screen Projection (VREX)

No significant difference in PER between the head-mounted display and the on-screen projection was seen in this data set across the group (Figure 13). Not all individuals had equal PERs between displays – two subjects had significantly different PERs between displays. One subject had a much greater PER when viewing the on-screen projection as compared to the head-mounted display. A second subject had the opposite trend.

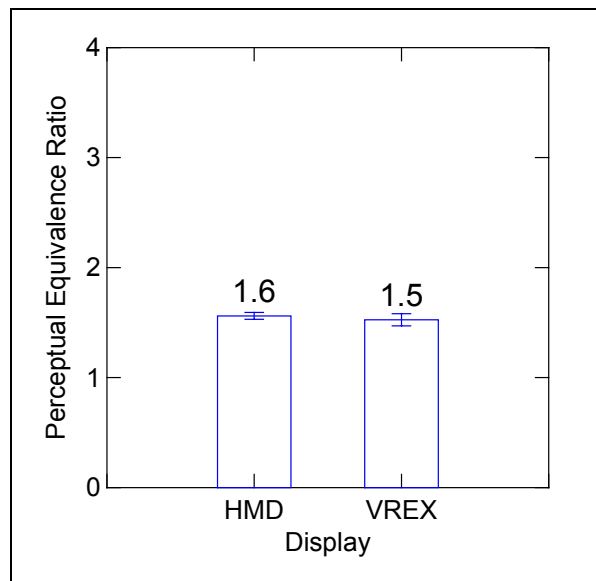


Figure 13. Experiment 2: PER (Mean  $\pm$  SEM), Head-Mounted Display (HMD) vs. On-screen Projection (VREX)

### 5.2.1.2 Treadmill Speed

There was a significant effect of treadmill speed on PER ( $F(2, 12) = 12.522$ ;  $p = 0.008$ ) (Figure 14). Contrasts between adjacent treadmill speeds showed significant differences between them. Unlike the previous experiment shows that PER is not invariant across the tested treadmill speeds, but varies by a small amount. Each individual subject showed reduced PER at one intermediate speed.

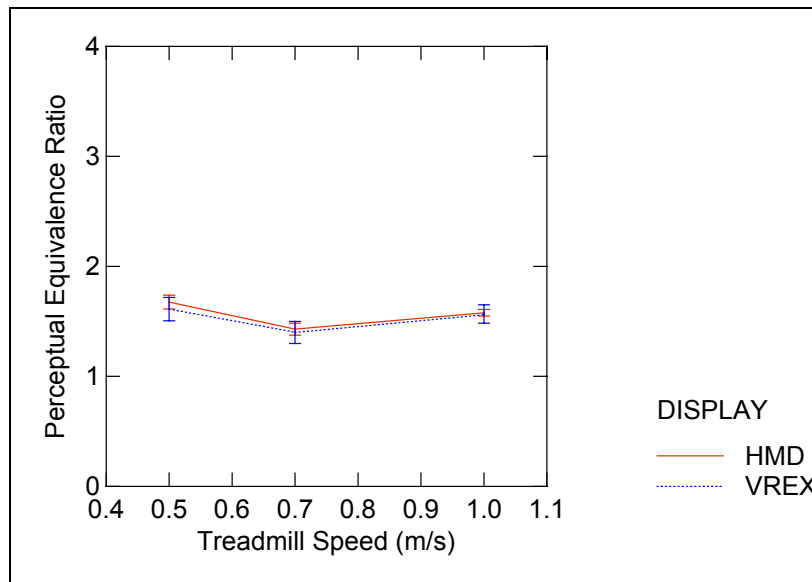


Figure 14. Experiment 2: PER vs. Treadmill Speed (Mean ± SEM)

This main effect of treadmill speed, however, is the result of a more significant temporal effect. A non-parametric Page test found a highly significant decreasing trend in PER with trial number both for the head-mounted display ( $p < 0.00005$ ) and for the on-screen projection ( $p = 0.0004$ ) (Figure 15).



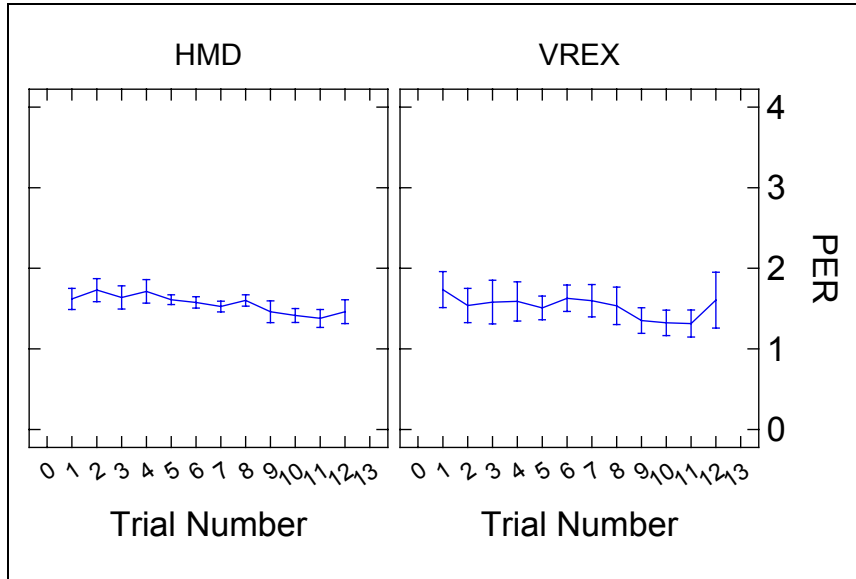


Figure 15. Experiment 2: PER (Mean  $\pm$  SEM) by Trial Number

### 5.2.1.3 Between- and Within-Subject Differences

Once again, as seen in the previous experiment, the differences in average PER between subjects were large compared to the variances of PER measured within any individual subject (Figure 16, Figure 17 and Figure 18).

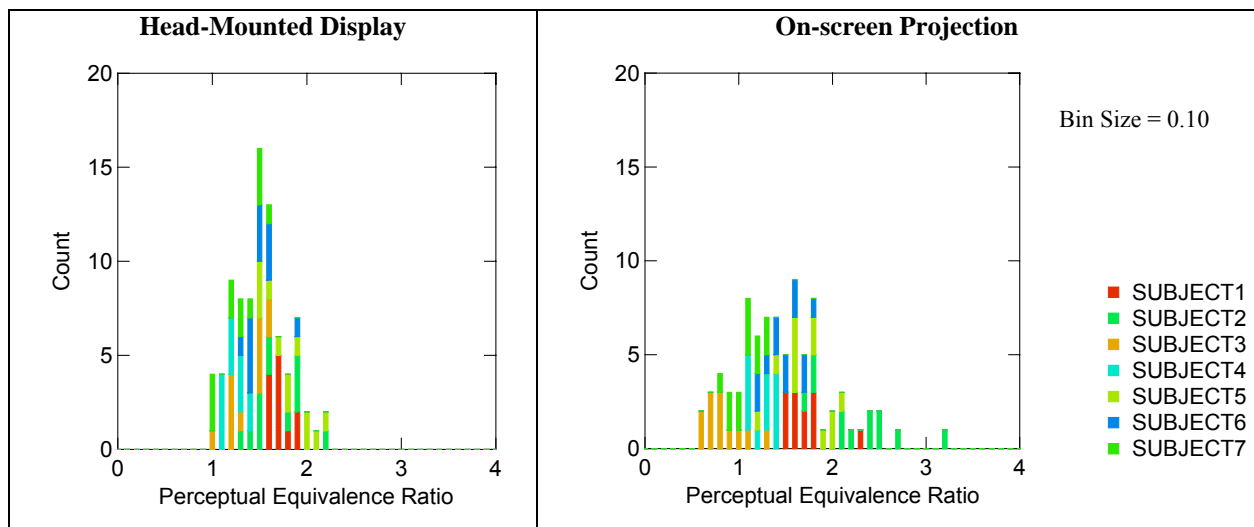


Figure 16. Experiment 2: PER Histograms, Head-Mounted Display (Left) and On-screen Projection (Right)

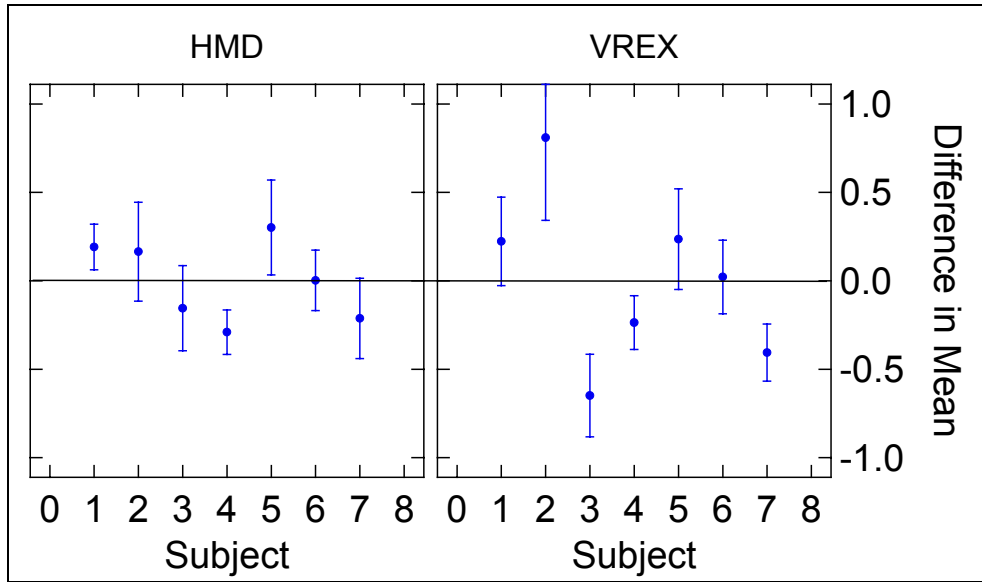


Figure 17. Experiment 2: Average PER by Display (Mean ± SD), Each Subject compared to the Overall Average

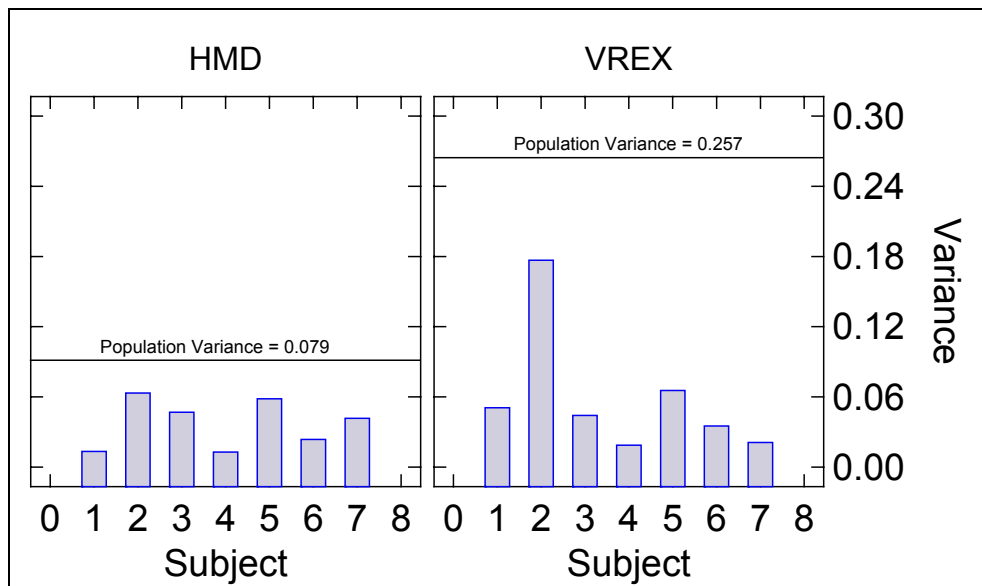


Figure 18. Experiment 2: Variance in PER, Each Subject compared to the Overall Variance

## 5.2.2 Presence

### 5.2.2.1 Head Mounted Display (HMD) versus On-screen Projection (VREX)

Six of the seven subjects reported greater presence when wearing the head-mounted display than when viewing the on-screen projection ( $F(1,6) = 6.644$ ;  $p = 0.042$ ) (Figure 19). This trend between displays was in the direction predicted.

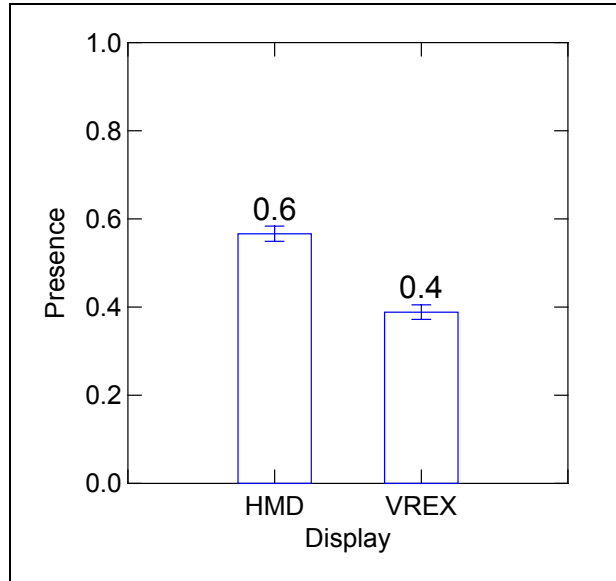
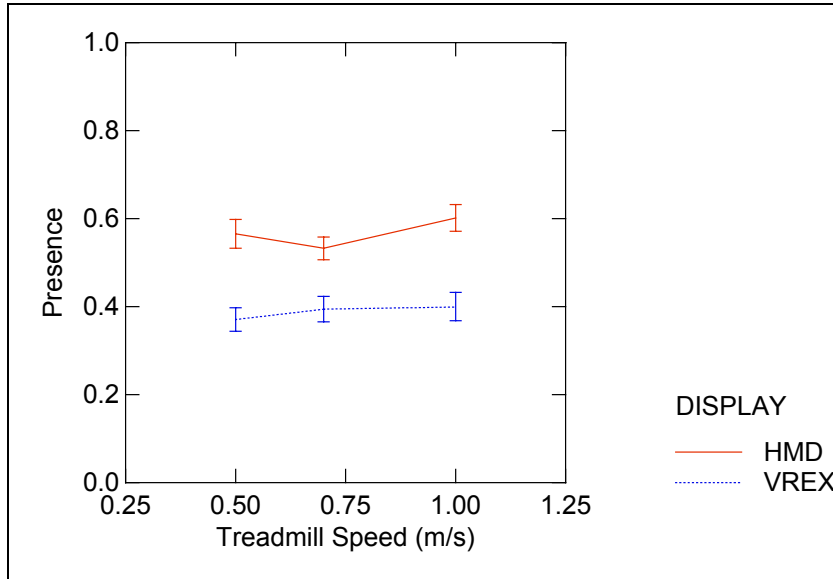


Figure 19. Experiment 2: Presence (Mean  $\pm$  SEM), Head-Mounted Display (HMD) vs. On-Screen Projection (VREX)

### 5.2.2.2 Treadmill Speed

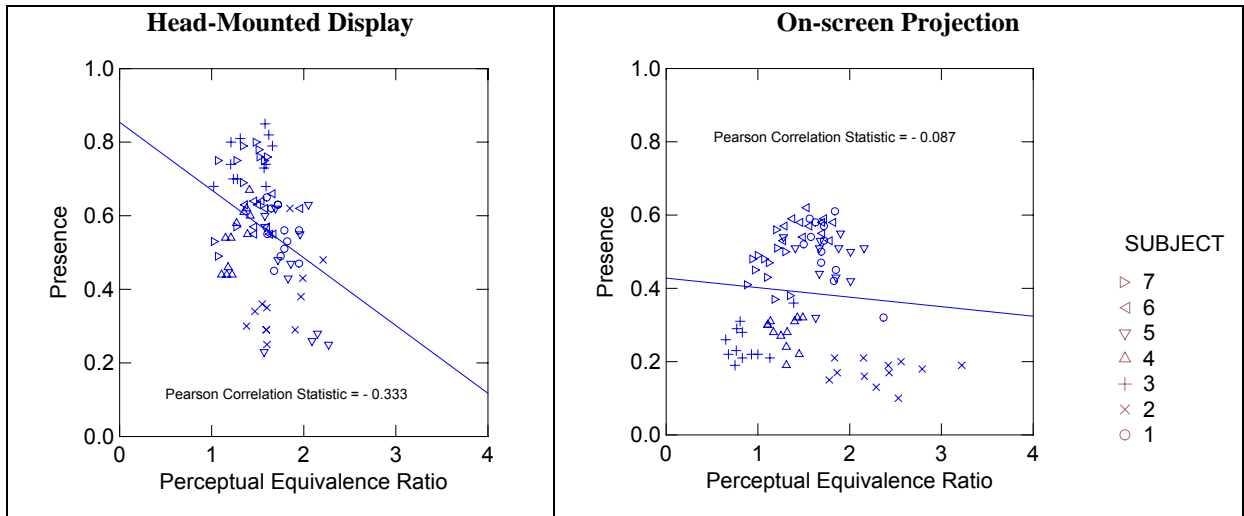
As opposed to the PER measure, there was no significant main effect of treadmill speed on presence (Figure 20). Within each display, presence was relatively insensitive to changes in treadmill speed. As in the previous experiment, presence is nearly invariant across the selected treadmill speeds.



**Figure 20. Experiment 2: Presence vs. Treadmill Speed (Mean ± SEM)**

### 5.2.3 Correlation Between PER and Presence

A linear regression found a negligible (correlation coefficient = -0.333) but statistically significant trend between PER and presence (Slope =  $-0.60 \pm 0.19$ ;  $p = 0.002$ ) when wearing the head-mounted display (Figure 21). When viewing the on-screen projection, no dependence of PER on presence was found. This result is in the opposite direction from the head-mounted display versus desktop monitor experiment (Experiment 1), but the low correlation coefficient observed in both experiments suggest that presence and PER are weakly and inconsistently correlated.



**Figure 21. Experiment 2: Correlation between PER and Presence, HMD and On-screen Projection**

### 5.3 Repeatability of the PER Measure Between Sessions

The four subjects that participated in both Experiment 1 and Experiment 2, conducted three months apart, were compared for consistency of their PER over time on their repeated experiments with the head-mounted display (Figure 22 through Figure 25). No consistent pattern was found. Subjects 1 and 3 showed significant increases in PER from the first (Experiment 1: head-mounted display versus desktop monitor) to second (Experiment 2: head-mounted display versus on-screen projection) experiment (t-test;  $p < 0.05$ ). Conversely, Subjects 2 and 4 showed significant decreases in PER from the first to second experiment (t-test;  $p < 0.05$ ).

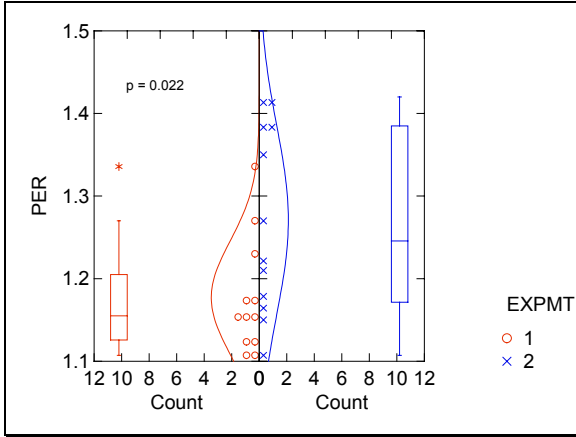


Figure 22. PER Repeatability, Subject 1

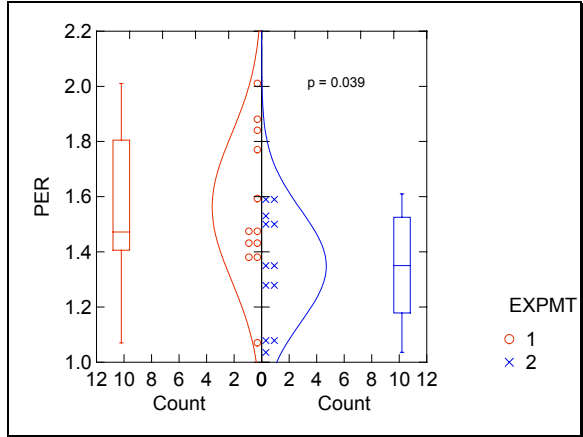


Figure 23. PER Repeatability, Subject 2

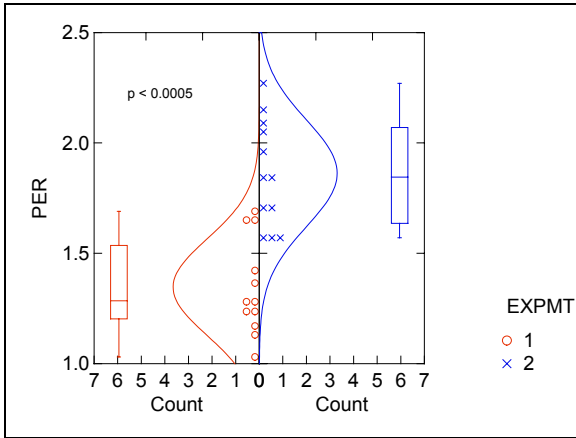


Figure 24. PER Repeatability, Subject 3

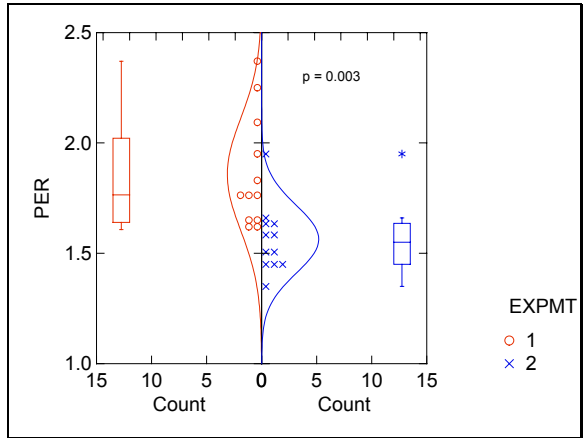


Figure 25. PER Repeatability, Subject 4

## 5.4 Experiment 3: Visual and Treadmill Speed Matching for Perceptual Equivalence

### 5.4.1 Perceptual Equivalence Ratio (PER)

The data set was structured as a three-factor repeated measures analysis across Method (2 levels), Treadmill Speed (3 levels), and Repetition (2 levels). The two adjustment methods, as mentioned in the Methods section are either V(T) (visual adjust) or T(V(T)) (treadmill adjust). That is, either adjusting the visual speed to match a fixed treadmill speed (visual adjust; V(T)), or adjusting the treadmill speed to match the fixed visual speed (treadmill adjust; T(V(T))). Each participant repeated each stimulus condition two times. The repeated measures data was analyzed using a General Linear Model (Systat v10).

#### 5.4.1.1 Visual or Treadmill Adjustment

No significant main effect of method on PER was found (Figure 26). Therefore, it can be said that PER is largely independent of whether the visual speed was adjusted to match a fixed treadmill speed (visual adjust), and whether the treadmill speed was adjusted to match a fixed visual speed (treadmill adjust).

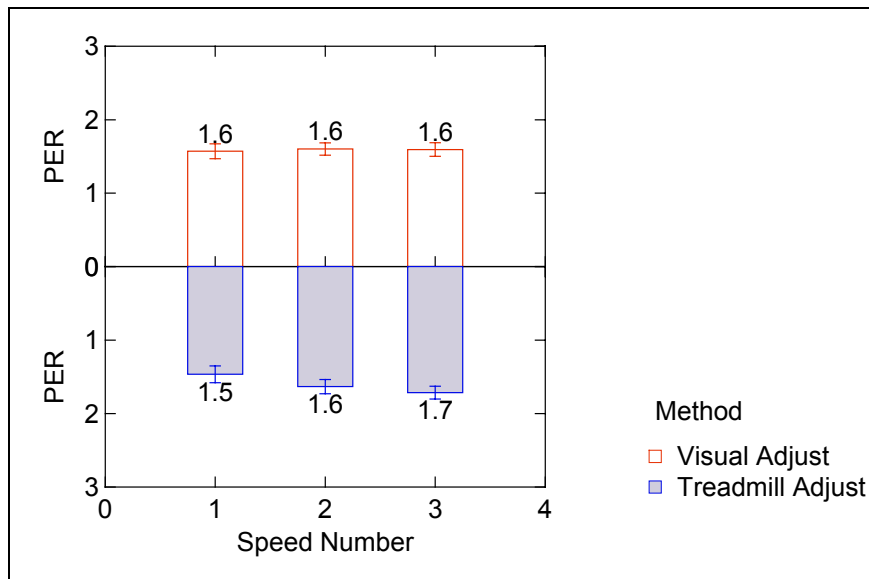
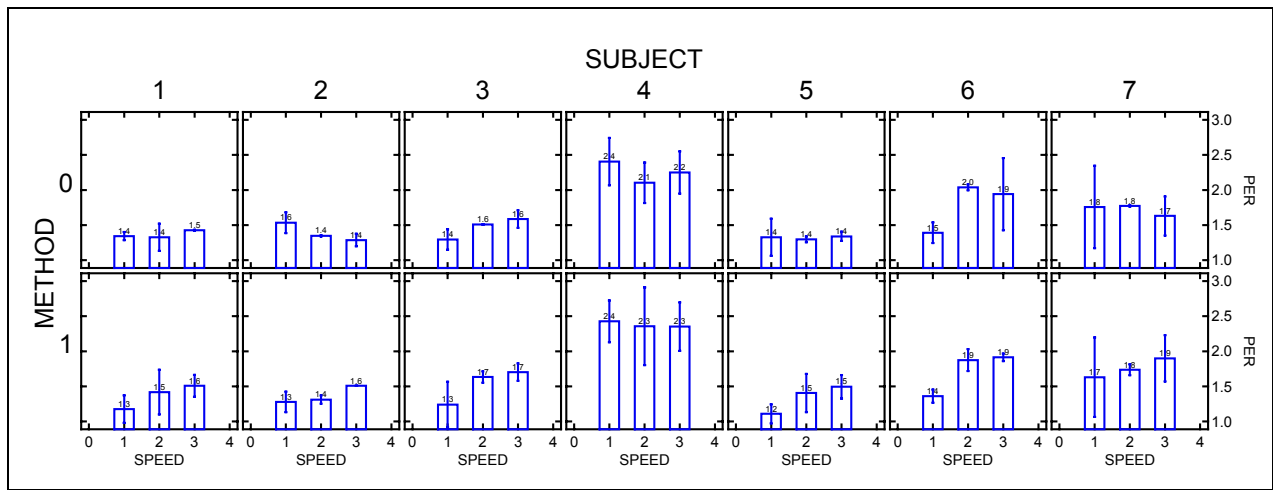


Figure 26. Experiment 3: PER (Mean ± SEM) vs. Speed Number, Visual and Treadmill Adjustment Methods

### 5.4.1.2 Treadmill Speed

There was no significant main effect of speed on PER. The preceding figure shows PER is relatively constant across the three speeds tested (1.4, 2.0, 2.8 mph).

Although there was a significant method\*speed cross-effect ( $F(2,12) = 8.56$ ;  $p = 0.005$ ), it appears to be due to two of the seven subjects (subjects number 2 and 7) and is not seen in the others (Figure 27). A larger study would be needed to explore the effect.



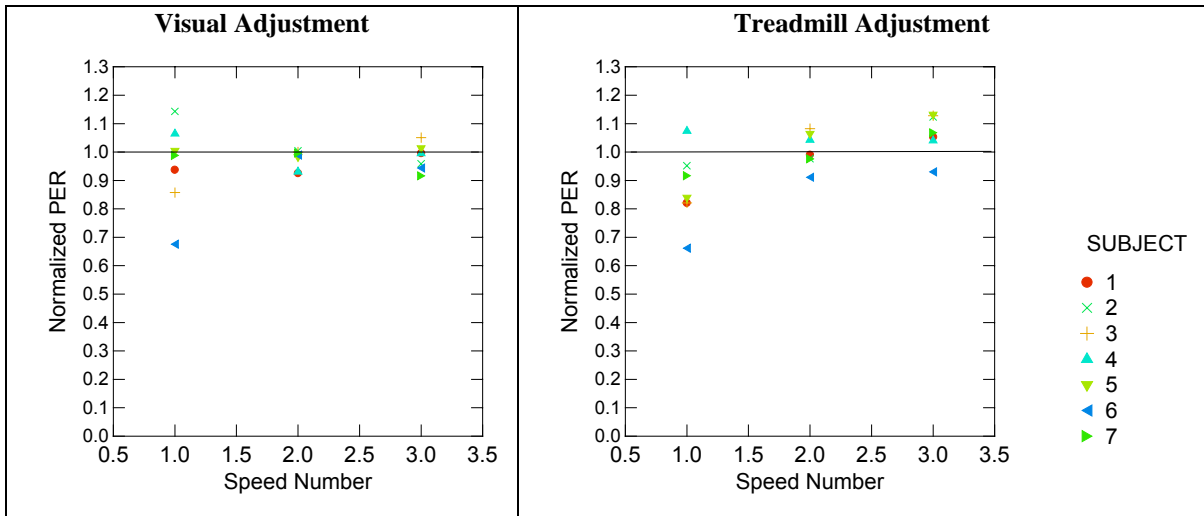
**Figure 27. Experiment 3: Subject-by-Subject PER vs. Speed Number (Mean ± SEM) (Method 0 = Visual Adjustment, Method 1 = Treadmill Adjustment)**

### 5.4.1.3 Constancy of PER over Trials

To separate the effect of subject from the effect of constancy within a subject’s trials, the PER values were normalized to the PER value the subject reported on the first trial. This was done by dividing each subjects data by the PER value from their first trial (“normalizing PER”), so that the resulting normalized value showed the magnitude of PER change relative to the first trial value for that individual subject. The normalizing PER values ranged from 1.3 to 2.3. The normalized PER values were grouped by speed, although speed was not always a constant. We observed that the normalized PER varied slightly in method 1 reporting (adjust the treadmill speed to match a fixed visual speed) (Figure 28). Collected locally for different speeds, the normalized PER values are understating their own constancy since we would expect those PER values, drawn from slightly different speeds, to differ from one another. We find, however, that the



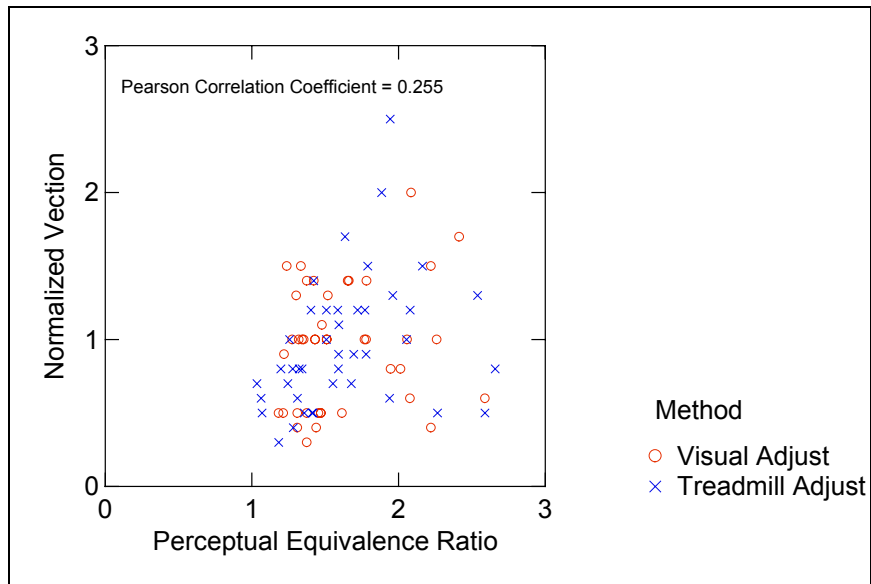
normalized PER is approximately constant across speeds. That is, it maintains, roughly, the value ‘1’ it had for the first trial. This supports the belief that the reported PER values are approximately constant across speeds for a given subject in a relatively short experiment. The figure below (Figure 28) shows the normalized PERs. The clustering of each subject’s normalized PER about the value 1 indicates the degree of constancy in PER seen in the experiment.



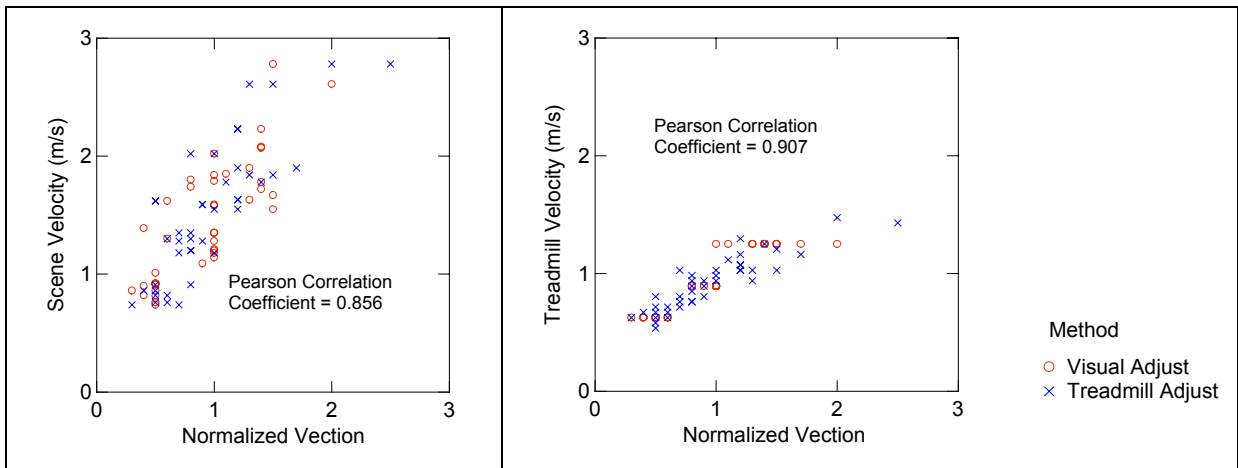
**Figure 28. Experiment 3: Normalized PER vs. Speed Number, Visual and Treadmill Adjustment (Repetitions Averaged)**

#### 5.4.2 Correlation between PER and Vection Magnitude

The vection magnitude reports were normalized to the modulus. This kept the values the same order of magnitude as the scene and treadmill speed, and the PER reports. There was no strong correlation between PER and vection magnitude reports (Pearson Correlation coefficient = 0.255) (Figure 29). The correlations between vection and scene speed (0.856) or treadmill speed (0.907) were larger (Figure 30).



**Figure 29. Experiment 3: Normalized Vection Reports vs. PER**

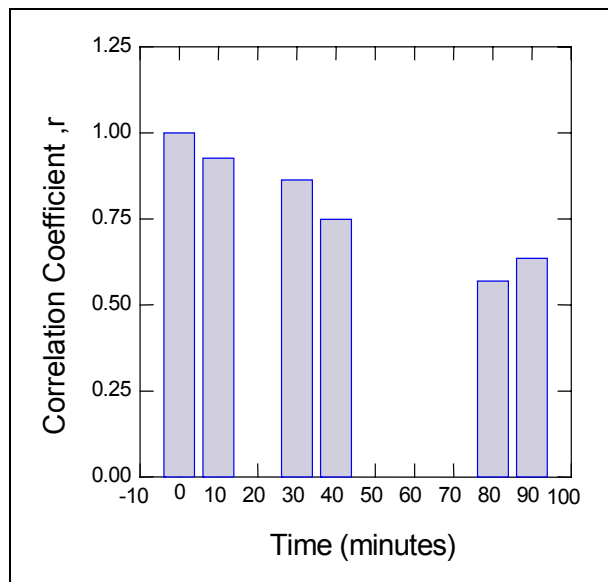


**Figure 30. Experiment 3: Correlation between Normalized Vection and Scene- and Treadmill-Speed**

### 5.5 Experiment 4: The Effect of Working Memory on PER

Once again, to separate the effect of subject from the effect of phase within each subject's trials, the PER values were normalized to the PER value reported on the very first trial. These normalizing PER values ranged from 1.2 to 3.5 for the ten subjects tested.

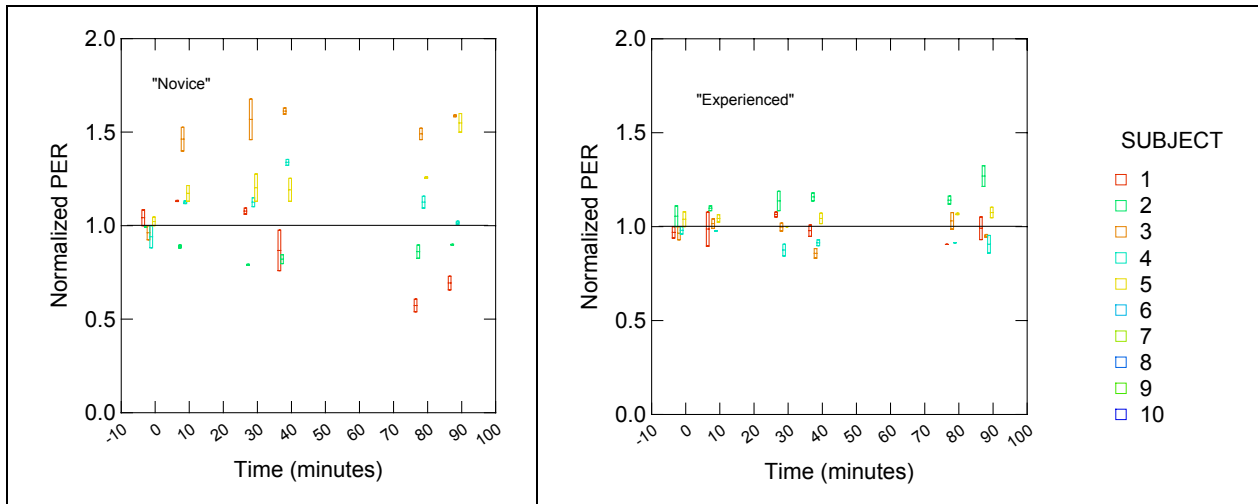
Throughout this 90-minute experimental session, normalized PER values tended to increasingly deviate from 1, the normalized value seen on the very first trial. Figure 31 shows that as time progresses, PER values tended to correlate less with their initial value. After approximately eighty minutes, the Pearson correlation coefficient drops to its lowest value, 0.57, which indicates a weak relationship with the first reported PER value. The changes in the correlation coefficient suggests changes in PER over time periods as short as ten minutes.



**Figure 31. Experiment 4: Correlation Coefficient, r, with Initial PER Values**

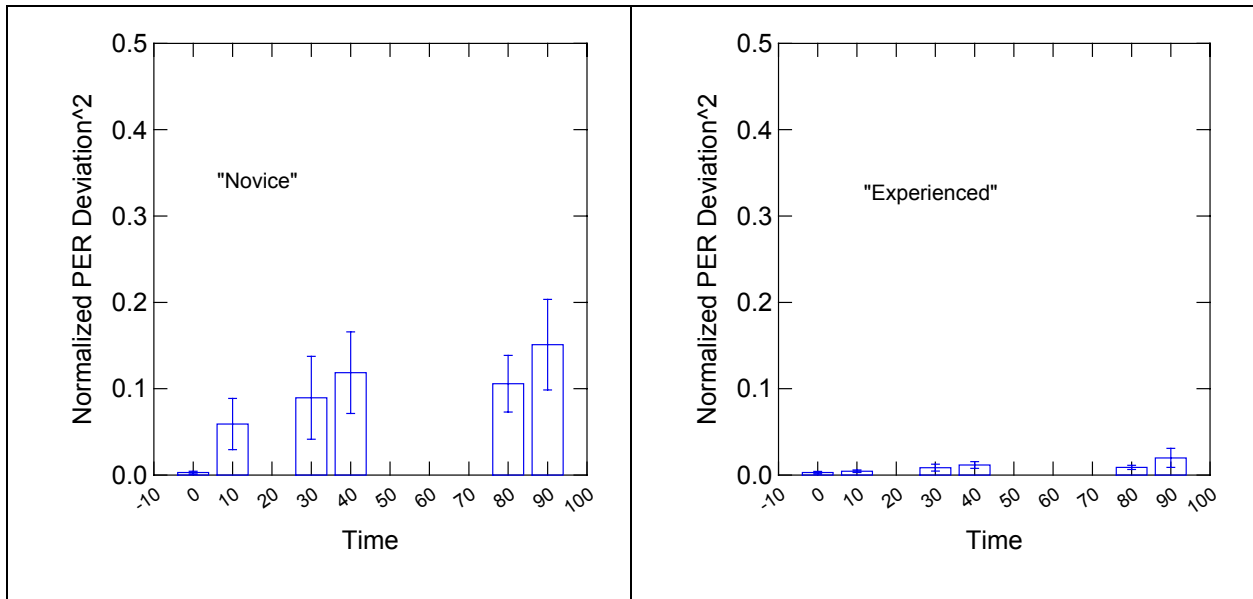
There were two classes of subjects: those (“experienced”) who had taken part in an experiment measuring PER several months prior, and those (“novice”) who had not. Figure 32 qualitatively shows the difference in constancy between novice and experienced subjects. The short width of the box plot indicates that a subject is relatively consistent in PER judgments from rep-to-rep (recall that there are two repetitions at each time interval).

The experience of each subject seemingly has an effect on the stability of PER over time. The variance in the normalized PER repetition medians (average of two trials at each time interval), suppressing time variation, for experienced subjects (ranged from 0.001 to 0.005) was significantly less than that of the novices (ranged from 0.005 to 0.060) (Kruskal-Wallis;  $p = 0.016$ ).



**Figure 32. Experiment 4: Normalized PER vs. Time**

The relationship between the square of the deviation in normalized PER (“nPER”) from 1 (“squared deviation” =  $(nPER - 1)^2$ ) and time was analyzed using a nonparametric Page test, which tests for monotonicity. The squared deviation of normalized PER increased for both experienced (Page Test:  $p = 0.0003$ ) and novice subjects (Page Test:  $p = 0.0002$ ) as the experiment progressed (Figure 33).



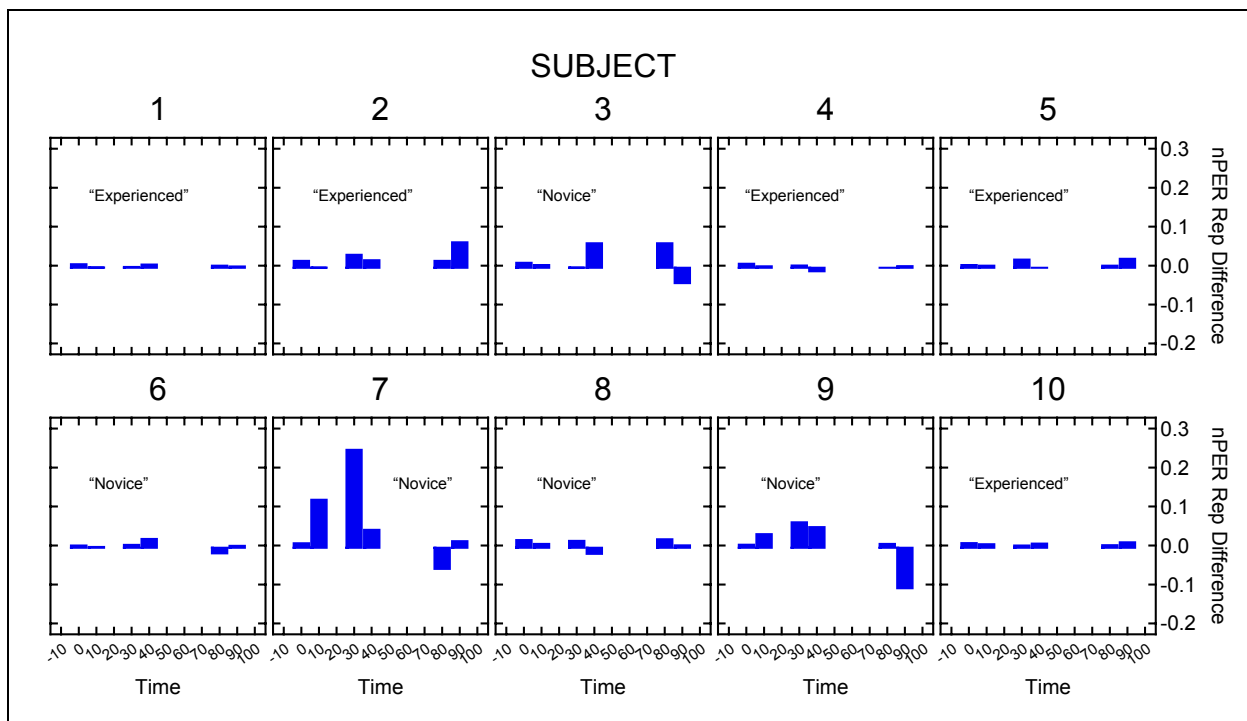
**Figure 33. Experiment 4: Normalized PER Squared Deviation vs. Time (Mean  $\pm$  SEM)**

A nonparametric Kruskal-Wallis test found that the squared deviation for experienced subjects was significantly smaller than that of the novices for three of the five time intervals, i.e. at 10-, 40-, and 80-, but not at 30- or 90-minutes (Table 4). The overall trend, evident in Figure 32, however, is unusually strong even if it does not prevail at every time-interval. Assuming that the trials at the different time-intervals are independent, the difference between the two groups considering the whole family of comparisons is highly significant. The probability that 3 or more tests out of 5 would be significant at the 0.05 level (on the null hypothesis that there is no effect of experience) is only  $p \leq 0.0012$ , which makes the family result significant.

**Table 4. Kruskal-Wallis p-values, Experienced vs. Novice Subjects (Normalized PER Squared Deviation vs. Time)**

Time (minutes)	Rep Median
0	p = 0.917
10	p = 0.009
30	p = 0.076
40	p = 0.009
80	p = 0.016
90	p = 0.251

There was no significant effect of experience at intervals of 30- and 90-minutes, but those intervals happen to correspond precisely to the most prominent outlying results – those of Novice subject 7 at 30-minutes, and of Novice subject 9 at 90-minutes (see Figure 34). This suggests that a single outlying repetition might (in each case) have caused each of those very large differences between repetitions. With only five subjects in each group, those differences might have shifted the mean of the two repetitions and that shift may have disturbed the rank of its subject and upset a precarious trend. No significant effect of experience, however, is found when rep 2 at 30-minutes (subject 7) and rep 2 at 90-minutes (subject 9) are deleted. The effect of experience, evident in Figure 33 and Table 4, is well represented by the significant family result for three of the five time-intervals.



**Figure 34. Experiment 4: Normalized PER Repetition Difference (Rep 1 minus Rep 2)**

## 6 DISCUSSION

### 6.1 Factors Affecting PER

A set of four experiments explored several factors that may affect the reliability of the PER measure. These factors include, but are not limited to, the display type, the sense of presence, treadmill speed, and the strategies used by the subjects, which may be related to experience and/or the limitations of working memory. This section discusses how these factors may have affected PER, either independently or in a coupled fashion.

#### 6.1.1 Display Type

Experiments 1 and 2 sought to determine the effects of display type on PER. In Experiment 1, the difference in PER (in the direction opposite to that hypothesized) between the head-mounted display and the desktop monitor may have resulted from differences between the displays. There are at least five factors that may have contributed: 1) field-of-view, 2) view of the ambient environment, 3) experiment design, 4) perceived image stability, and 5) stereoscopic vs. monoscopic projection.

##### 6.1.1.1 Field-of-view

It was thought that the size of the horizontal (and vertical) field-of-view of the projected environment would be the most important contributor to the difference in PER between displays. We did find a significant difference (head-mounted display vs. desktop monitor), but PER decreased for a smaller field-of-view, which was not in the predicted direction (as discussed in Section 3). Since PER values for the desktop monitor (24°H x 18°V field-of-view) were less than those for the head-mounted display (48°H x 36°V), factors other than the size of the field-of-view must be contributing to these differences.

##### 6.1.1.2 View of the Ambient Environment

The shroud on the head-mounted display prevented subjects from viewing the surrounding laboratory environment in their peripheral vision. By contrast, the light emitted by the desktop monitor did allow a dark-adapted subject to see portions of the

laboratory environment, including where his feet were falling, in his peripheral vision. This view could allow him to estimate his stride length and might, therefore, contribute to the difference in PER between the displays. It does not, however, directly explain the direction of the effect. The magnitude of the effect, if any, cannot be estimated from the data. In Experiment 2, the on-screen projection emitted light, as the desktop monitor did, but this did not appear to affect PER values.

#### **6.1.1.3 Experiment Design**

In Experiment 1 (and in Experiment 2), the subjects were always tested first with the head-mounted display. Therefore, we cannot rule out an order effect, i.e., the possibility that adjusting the scene speed while wearing the head-mounted display had an effect on later trials in which the subjects viewed the desktop monitor (or the on-screen projection).

#### **6.1.1.4 Perceived Image Stability**

The lack of stability in the perceived image may also have also contributed to the differences in PER between display types. When subjects wore the head-mounted display, the projected image seemed to move slightly relative to the unseen world due to the natural head motions associated with walking. (In pilot trials, a 3-degree-of-freedom inertial head-tracker did not reduce this relative motion of the projected image and was, therefore, not used in the full experiments.) The image on the desktop monitor or on-screen projection, however, did not produce any such apparent motion of the image relative to the laboratory environment. Although these motions of the head-mounted display image were perpendicular to the movement of the virtual environment, we cannot rule it the possibility that they contributed to the effect of display type on PER.

#### **6.1.1.5 Stereoscopic vs. Monoscopic Projection**

The vection literature has long asked how does a stereoscopic or monoscopic projection affects our perception of self-motion. This question arises again in the results presented here. The head-mounted display always presented the visual image stereoscopically, whereas the desktop monitor and on-screen projection were both monoscopic. This



present data cannot, unfortunately, resolve the different effects of stereoscopic vs. monoscopic projection on PER, vection magnitude, or even on the sense of presence because projection type (monoscopic/stereoscopic) was not manipulated within any particular display. The data suggests that the projection type does not have a profound effect on PER: Displays with the same fields-of-view produced the same PER values even though one (head-mounted display) was stereoscopic and the other (on-screen projection) was monoscopic. Earlier experiments have found, however, that a stereoscopic projection of a virtual environment provides a greater sense of presence (Ijsselsteijn et al., 2001) and gives a perception of speed greater than the same environment projected monoscopically does (Palmisano, 2002).

### **6.1.2 Presence**

The first two experiments also sought to determine the relationship, if any, between PER and the sense of presence. Experiment 1 found that both PER and presence were significantly different between the head-mounted display and the desktop monitor -- PER and presence were both lower when viewing the desktop monitor compared to the head-mounted display. This finding suggested that there might be a relationship between the two dependent measures, especially since their trends between the two displays were in the same direction. However, the weak (and non-significant) correlation between PER and presence for each display leads us to believe there is no influence of presence on PER. Recall that PER values were constant between displays with the same horizontal field-of-view even though the sense of presence was significantly different (Experiment 2). It can, therefore, be said that the sense of presence probably does not affect PER values, but rather PER is affected by the display used to project the virtual environment.

Presence likely does not affect PER since, when the subjects matched the scene and treadmill speeds for perceptual equivalence, their perception of speed likely was based on the assumed eye height (it was obvious that the virtual viewpoint was appropriate) and the estimate of the size of objects (which they knew were of familiar size) in the virtual environment, and not the sense of “being there.” It is possible that the subjects felt an increased sense of presence in this virtual environment (as compared to an abstract one) because they knew the objects in the virtual environment were familiar and of known size. These objects, however, were not manipulated

within the experiment. This likely contributed to the subject's sense of presence being relatively constant (across treadmill speeds) within a particular display.

### **6.1.3 Treadmill Speed**

All of the experiments found that the treadmill speeds used did not have large effects on either PER or presence. In Experiment 2, there was a significant effect of trial order on PER, which at first appeared to be a main effect of treadmill speed. This effect probably arose due to the blocking of treadmill speeds in the experimental design, and hence on time and experience. If PER values were (significantly) dependent on treadmill speed (which they are not), then vection magnitude reports (Experiment 3) would have indicated that subjects misperceived their apparent speed of self-motion.

### **6.1.4 Experience, Strategies, and Working Memory**

The aim of Experiment 4 was to find the reason(s) why the four subjects common to two of the previously discussed experiments (Experiments 1 and 2) had significantly different PER reports between the two sessions (that were three months apart). Both of these data sets (Experiments 1 and 2, and Experiment 4) showed that PER is variable over time, and the magnitude of this variability seems to depend partly on the experience of the subject. Subjects who had taken part in at least one experimental session (experienced subjects) often had much smaller deviations in their PERs from those on the very first trial throughout a 90-minute experimental session than those subjects who had never took part in a PER experiment (novice subjects). As the experiment progressed, the PER values for both types of subjects tended to deviate further from that reported on the very first trial.

There are several possibilities for this variability in PER with time. It is possible that the subjects are forgetting the strategy used, such as attending to different cues, or perhaps objects, in the virtual environment between sessions as a result of the limitations of our working memory. We saw that after approximately 80-minutes, within the same session, the Pearson correlation coefficient dropped to its lowest value of 0.57 (Figure 31). It could be speculated that if the experiment were to extend past 90-minutes, the correlation coefficient would approach zero.

This would be consistent with the idea that the subject has forgot the initial strategy used when making PER judgments.

If working memory is at fault for these changes, then consistent performance would be expected from rep-to-rep (i.e., minute-to-minute) since the decay of information that requires central processing is minimal provided that rehearsal is possible (Laabs, 1973). One possible strategy may use verbal information, such as counting strides or time between passage of salient objects in the scene and memorizing the resulting number, when adjusting scene (or treadmill) speeds for perceptual equivalence. If this is the case, then retention performance may follow that of verbal short-term memory (Laabs, 1973), where recall accuracy decays exponentially with time. Retention performance (memory decay), experience of the subject in PER experiments, and the cues the subjects are attending to all likely contribute to the changes we see in PER over time. Choosing the cues to attend to, however, may come from experience. We cannot, unfortunately, distinguish one factor from another as all may be at work simultaneously.

## **6.2 Limitations and Uses of PER**

Even though a set of conditions have been explored where PER appears to be constant, the repeatability of PER must be considered. This section not only addresses some of the limitations of PER, particularly related to its variability, but also discusses the use of PER for quantifying oscillopsia.

### **6.2.1 Repeatability of PER**

PER within an experimental session is, perhaps, not as precise as one might assume. The standard deviation in PER reports (e.g., Figure 8 and Figure 17) is often no better than 0.2 (roughly 20% of the average), even for the most experienced subjects. This indicates that the match between scene and treadmill speed is difficult to perceive and adjust reliably. If the subject has sufficient experience in making PER judgments, and the difference in average PER between sessions is larger than the within-session variance, then scene speed calibration should be considered each time the user enters the virtual environment. Designers of virtual environments who desire perceptual equivalence should calibrate the scene speed of the virtual

environment based on the PERs of each individual user, who is sufficiently trained, and be aware that the subject's calibration may change over time.

### **6.2.2 Between- and Within-Subject Differences**

Both Banton et al. (2003) and Jaekl et al. (2002) reported that a large range of visual motions were judged correct for the accompanying self-generated physical motions in a given virtual environment. They grouped all the measurements without distinguishing within- from between-subject differences. If they used novice subjects (those who had not taken part in a PER experiment before) they may not have been able to distinguish within- from between-subject differences, primarily because of the large variances in their PER reports. The experiments in this thesis (particularly Experiments 1 and 2) make an attempt at this distinction. Even though, in large part, the subjects in these experiments are novices, the large differences in average PER between subjects compared to the variances of PER within any individual subject hints at the need to calibrate the virtual environment setup for each user separately.

### **6.2.3 Simulation, Training, and Entertainment**

Before applying a scene speed that is either faster or slower than one is actually moving, the appropriate speeds to use should be thoroughly researched in each setting. We have seen here (and in other studies, e.g., Banton et al., (2003)) that, on average, the scene speed should be greater than treadmill walking speed for perceptual equivalence. This may not, however, be the case in all virtual environments. The virtual environment scene speed calibrations for extra-vehicular activity training, and those in walk-about simulations used by the military may be different from those in flight simulation, assuming scene speed calibrations are necessary for these applications. A properly adjusted scene speed may improve performance in training situations where speed perception, and time to contact judgments are crucial (e.g., driving and flight simulation).

The commercial (gaming) industry could also make use of PER values. In games involving simulated self-motion, the users may feel as though they are moving 10 to 30% slower than in the real world if scene speed adjustments are not introduced (based on PER values) to compensate for field-of-view restrictions. This may lead to an experience that does not feel real.

Games with properly adjusted PERs may improve the overall experience, and therefore, the marketability of the game.

#### **6.2.4 Quantifying Oscillopsia**

The PER measure, as defined in this thesis, may lead to a way of quantifying the magnitude of oscillopsia during walking. It can be speculated that all of us, whether we acknowledge it or not, may have very mild oscillopsia, which we have learned to ignore. PER values in a virtual reality environment, particularly when the vestibular and haptic systems are stimulated, may give us insights to how the visual, haptic, and vestibular systems are reacting to the perceptions in this artificial environment. If we can understand how the human brain integrates the sensory perceptions in virtual reality settings, and perhaps any time course of this change (particularly for spaceflight-related oscillopsia), then we may be well on our way to reducing the occurrence of and compensating for this clinical condition.

### **6.3 Future Work**

Future experiments could consider the following changes:

- Project the virtual environment both stereoscopically and monoscopically in each display used, instead of, for example, using the head-mounted display in stereo mode and the desktop monitor (or on-screen projection) in mono (e.g., Experiment 1).
- Use various sizes of field-of-view within the head-mounted display. One condition might use the full horizontal and vertical field-of-view, and a second project the same image using a fraction of the available field-of-view.
- Suggest a strategy (or strategies) for making PER judgments. One might suggest that a subject match his estimated stride length to the dimensions of an object of known size in the virtual environment: For example, suggest that the subject ask himself, “How long is my stride relative to the first door on the right-hand-side of the hallway (see Figure 2)? When I take a step, does the visual scene move this distance? If not, adjust the scene speed until it does.” If the subject reads a suggested strategy, and practices it on several trials, he/she may be more likely to use it in future sessions. This consistent use of a strategy might reduce the variability in PER between sessions.

- Keep the experiment as short as possible. We saw small changes in PER over time intervals as short as 10-minutes, and larger changes after approximately 40-minutes (Figure 31). In a longer experiment, however, greater variability in PER values is to be expected. This variability with time may be reduced if the subject uses a consistent reporting strategy (see previous bullet).
- Improve the image stability seen in the head-mounted display. This could be done by tightening the fit of the head-mounted display on the subject's head or by shortening the end-to-end latency of the virtual reality system. End-to-end latency is the length of time it takes the tracking system to process the position and orientation information caused by the subject's head movements and then to render the virtual environment. Banton et al. (2003) had end-to-end latencies of approximately 100-milliseconds, but did not suggest that this long latency affected his results. The end-to-end latencies in the present pilot experiments were at least 50-milliseconds (at least 10-milliseconds tracker delay (Intersense IS-600 Mark 2 Plus) and 40-milliseconds in graphics rendering delay). We would want a minimum system update rate of 60 Hz<sup>1</sup> to rule out update rate as a potential confounding variable in PER experiments. If we need to update the scene at 60 Hz, then we would want the end-to-end latency to be no greater than approximately 20-milliseconds. The V8, and other head-mounted displays have a maximum refresh rate of 60 Hz, which would make it difficult to exceed this rate. To make the virtual environment as "real" as possible, it would be profitable to improve the rendering time and reduce any delays in the head-tracker system, if one is used.

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<sup>1</sup> The fastest stride frequency is approximately 3 Hz, and the high-frequency component of the subject's pitch head motions is likely ten times the stride frequency, or 30 Hz (30 Hz was the maximum update rate in these experiments). For adequate data sampling, the sampling frequency should be at least twice the highest frequency component you expect, in this case at least 60 Hz (= 2 x 30 Hz).

## 7 CONCLUSIONS

Four experiments investigated the conditions under which the ratio of the visual speed of the virtual environment to that of the treadmill walking speed (defined as the perceptual equivalence ratio (PER)) is constant. In the conditions where PER was found to be variable, the mechanisms causing that variability were explored. These experiments investigated the relationship between PER and display type (head-mounted display vs. either desktop monitor or on-screen projection), sense of presence in the virtual environment, and the magnitude of illusory self-motion (vection). We also investigated differences among subjects, and the stability of PER over time due to the limitations of working memory.

These findings, collectively, are important for a perceptually sensitive environment, such as virtual reality that is so widely used for training, research, and entertainment. The concept of PER, particularly for constant velocity walking, has been studied only recently in virtual reality research. The experimental and practical settings where this ratio should be taken into consideration have not been completely defined, but its uses could range from training situations using virtual reality to quantifying (head-movement contingent) oscillopsia.

The main conclusions of these four experiments are listed below. We found that:

- display type had a significant effect on PER. PER values for the desktop monitor were approximately 15% less than those for the head-mounted display. The on-screen projection gave PER values similar to the head-mounted display.
- the sense of presence did not consistently correlate with PER. Therefore, we do not believe presence has a significant effect on PER based on the weak (and non-significant) correlation between the two measures.
- there was no significant effect of treadmill walking speed on PER over the range studied (1.1 – 2.8 mph).
- PER did not significantly depend on whether the visual or treadmill speed is manipulated (while the other is held constant).
- the difference in average PER between subjects was large compared to the variances in PER for any individual subject. Previous studies (e.g., Jaekl et al., 2002; Banton et al.,

2003) did not report the differences in perceptions of individual subjects versus those of the entire subject population. In this study, average PERs, for each subject individually, typically ranged from 1.1 to 2.0 with variances between 0.05 and 0.15.

- PER did not vary significantly over a short test session (less than 10 minutes), but was highly variable (less than 0.75 correlation with first trial) over extended periods of time (more than 40 minutes).
- in a 90-minute test session, subjects who had previously taken part in a PER experiment often had significantly less deviation in their reported PER from that on the very first trial than those who had never taken part in a PER experiment (after 90-minutes, squared deviation = 0.02 for experienced subjects vs. 0.15 for novices).



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# **APPENDIX A: Committee On the Use of Humans as Experimental Subjects (COUHES) Informed Consent**

## **MASSACHUSETTS INSTITUTE OF TECHNOLOGY DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS MAN-VEHICLE LABORATORY**

### **CONSENT TO PARTICIPATE IN BIOMEDICAL RESEARCH**

#### Role of Sensory Cues in Self-Motion Perception

You are asked to participate in a research study conducted by Kevin R. Duda, Charles M. Oman, Ph.D., and Andrew Liu, Ph.D., from the Man-Vehicle Laboratory in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (M.I.T.) You have been asked to participate in this study because you have normal or corrected-to-normal vision, have no vestibular or balance disorders, and no gait abnormalities. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

#### **• PARTICIPATION AND WITHDRAWAL**

Your participation in this research is completely VOLUNTARY. If you choose to participate you may subsequently withdraw from the study at any time without penalty or consequences of any kind. If you choose not to participate, that will not affect your relationship with M.I.T. or your right to health care or other services to which you are otherwise entitled.

#### **• PURPOSE OF THE STUDY**

In this study, we will be testing your perception of illusory self-motion (linearvection). Your various sensory systems – visual, vestibular, somatosensory, and proprioceptive – will be stimulated at some time during the experiment through the use of virtual reality and active locomotion. A sensory conflict exists when the current sensory cue(s) (afferent information) differs from the expected sensory cue(s) as predicted by the central nervous system (CNS) (efference copy). The relative importance of these sensory cues in the perception of motion, as well as whether the afferent information affects the CNS production of an efference copy is poorly understood. Through the use of virtual reality, we will be able to quantify the relative importance of sensory system cues in the perception of self-motion. The results from this study will be used to develop on-orbit and post-flight countermeasures for the astronauts, increase the fidelity of flight simulation, and provide additional insights into the neuroscience of self-motion perception to the vestibular community.

- **PROCEDURES**

You will be asked to participate in two sessions. The first is a training session, lasting approximately 15 minutes. The second is an experimental session, lasting approximately 75 minutes and involving up to 54 experimental trials, each lasting approximately 10-seconds, in which you will walk on a motor driven treadmill while wearing a head mounted display (HMD) with a light-occluding shroud.

In the training session, you will be asked to complete a history questionnaire which asks questions concerning your balance, vision, and susceptibility to motion sickness. If your questionnaire responses qualify you for the study you will be familiarized with the HMD itself, the treadmill and its range of speeds, and the reporting device (gamepad). During the experiment you will be wearing the HMD and shroud, and watch a computer generated visual scene that will move past you while you are either standing still or walking on the treadmill. Your head orientation will be tracked using a 3-DOF head tracker, and the visual display will be updated accordingly.

The experiment itself consists of a series of trials where the visual scene moves at different speeds. In each of these trials, you will continuously rate your sense of self-motion in the virtual environment (VE) using the game pad joystick with one hand while maintaining a hold on the treadmill handrail with your free hand. The joystick can be deflected in two axes; however, vection magnitude will be recorded by deflection on the positive y-axis (forward deflection). If you find yourself getting tired or fatigued and need a break, just ask for one. We can pause at any time. Best results are obtained from alert, energetic subjects.

After each trial, will ask you retrospective questions about your largest sense of presence (sense of “being there”) in the trial and your sense of self-motion (as a corroborative measure to the joystick rating). You are to answer each of the questions aloud and the experimenter will record and verbally confirm your response.

You will be wearing the HMD for approximately 90 minutes. If at any time you feel any discomfort as a result of the experimental protocol, you are free to take a break or discontinue and withdraw from the experiment at any time. At the conclusion of the experimental session, the experimenter will informally debrief you on your impressions, and discuss any difficulties that you may have encountered.

- **POTENTIAL RISKS AND DISCOMFORTS**

*Motion Sickness and/or Nausea*

If you feel any symptoms of motions sickness and/or nausea, mention them immediately to the experimenter. If the treadmill is in motion, it will be stopped immediately. The experimenter will assist you in doffing the head mounted display (HMD) and guide you to a seat until the symptoms subside.

### *Treadmill Dismount*

While wearing the HMD and shroud, your vision of the external world will be occluded and unless you keep one hand on the treadmill handrail, you will not know your position on the treadmill belt. This could result in an unanticipated lateral or aft stumbling or dismount with the possibility of injury. To prevent this, the experimenter will remind you to keep one hand on the handrail and the experimenter will watch you continuously. If you don't feel you can walk confidently, tell the experimenter immediately. Should you stumble (and subsequently fall), the experimenter will be close by and will catch you in your fall and stop the treadmill motion immediately.

### *Motion Aftereffects / Sensory Rearrangement*

You may have an illusory sensation of motion greater or less than your actual locomotion speed after completion of the experiment. This sensation usually subsides in less than twenty minutes. You should not ride a bike or operate an automobile within the 30 minutes immediately following the termination of the experiment.

### *Fast Walking Pace*

You will not be asked to walk faster than 3.6 mph in excess of 30-seconds. Locomotion at this pace may also be accomplished via a slow jog, however you should not jog while wearing the HMD. If you are not able to maintain a walking gait at this speed, you must inform the experimenter.

*The experiment may involve risks that are currently unforeseeable.*

## • **ANTICIPATED BENEFITS TO SUBJECTS**

You will not personally benefit from participating in this study. However, by serving as a subject, you will contribute new information, which may have benefits in the future.

## • **ANTICIPATED BENEFITS TO SOCIETY**

To date, no research has been done on the effects of active locomotion on the sensation of linearvection. Through understanding how the cues from the various sensory systems contribute to self-motion perception will be used to develop on-orbit and post-flight re-adaptation countermeasures for astronauts. The findings also have benefits in the flight and driving simulation domains.

## • **PAYMENT FOR PARTICIPATION**

Monetary compensation for those who are not members of the Man-Vehicle Laboratory (MVL) will be \$10 per hour. Subjects from the MVL will be taken on a volunteer basis and will not be paid. If you do not complete the study, you will be compensated for a minimum of a one-hour of participation and prorated for any time in excess of the minimum.

Due to INS and IRS restrictions, international students who are working at MIT more than 20 hours per week (e.g. as an RA or TA) are not eligible to receive additional compensation. If you chose to participate but are not eligible for compensation, line out the compensation sentence listed above.

- **FINANCIAL OBLIGATION**

You will not be billed for your participation in this research.

- **PRIVACY AND CONFIDENTIALITY**

The only people who will know that you are a research subject are members of the research team. No information about you, or provided by you during the research will be disclosed to others without your written permission, except: if necessary to protect your rights or welfare, or if required by law.

When the results of the research are published or discussed in conferences, no information will be included that would reveal your identity. If photographs, videos, or audiotape recordings of you will be used for educational purposes, your identity will be protected or disguised.

You will be given a subject number. All personal information, research data, and related records will be associated with this number. Your name and number will never appear on a distributed document together. Storage of the data will be in an electronic format on a secure computer that is only accessible by members of the Man-Vehicle Laboratory, and a hard copy will be bound and kept in a locked filing cabinet. If other research institutions have interest in the study, the results and/or you're data may be given to them without your notification. You're name and personal information (including medical history) will not be disseminated, only the data recorded during your participation in the experiment.



- **WITHDRAWAL OF PARTICIPATION BY THE INVESTIGATOR**

The investigator may withdraw you from participating in this research if circumstances arise which warrant doing so. If you experience any of the following side effects (dizziness, motion sickness, nausea and/or vomiting) or if you become ill during the research, you may have to drop out, even if you would like to continue. The investigator, Kevin R. Duda, will make the decision and let you know if it is not possible for you to continue. The decision may be made either to protect your health and safety, or because it is part of the research plan that people who develop certain conditions may not continue to participate.

If you must drop out because the investigator asks you to (rather than because you have decided on your own to withdraw), you will be paid proration as if you completed the study.

- **NEW FINDINGS**

During the course of the study, you will be informed of any significant new findings (either good or bad), such as changes in the risks or benefits resulting from participation in the research or new alternatives to participation that might cause you to change your mind about continuing in the study. If new information is provided to you, your consent to continue participating in this study will be re-obtained.

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, in either providing or making such medical care available it does not imply the injury is the fault of the investigator. Further information may be obtained by calling the MIT Insurance and Legal Affairs Office at 1-617-253-2822.

- **IDENTIFICATION OF INVESTIGATORS**

In the event of a research related injury or if you experience an adverse reaction, please immediately contact one of the investigators listed below. If you have any questions about the research, please feel free to contact one of the following:

Kevin R. Duda  
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Email: [amliu@mit.edu](mailto:amliu@mit.edu)

- **RIGHTS OF RESEARCH SUBJECTS**

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E32-335, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253-6787.

**SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE**

I have read (or someone has read to me) the information provided above. I have been given an opportunity to ask questions and all of my questions have been answered to my satisfaction. I have been given a copy of this form.

**BY SIGNING THIS FORM, I WILLINGLY AGREE TO PARTICIPATE IN THE RESEARCH IT DESCRIBES.**

\_\_\_\_\_  
Name of Subject

\_\_\_\_\_  
Signature of Subject

\_\_\_\_\_  
Date

**SIGNATURE OF INVESTIGATOR**

I have explained the research to the subject or his/her legal representative, and answered all of his/her questions. I believe that he/she understands the information described in this document and freely consents to participate.

\_\_\_\_\_  
Name of Investigator

\_\_\_\_\_  
Signature of Investigator

\_\_\_\_\_  
Date (must be the same as subject's)

## APPENDIX B: Virtual Environment and Medical History Questionnaire

### Role of Sensory Cues in Self-Motion Perception

Subject No.: \_\_\_\_\_

#### Personal Information

What is your gender?  Male  Female

What is your age? \_\_\_\_\_ yrs.

What is your height? \_\_\_\_\_  in.  cm

What is your weight? \_\_\_\_\_  lbs.  kg

What is your inseam? \_\_\_\_\_  in.  cm

What is your “handedness”?  Left  Right

#### Virtual Environment and Medical History Information

<p>1. Do you have medical conditions that would be aggravated if you became motion sick? <input type="checkbox"/> Yes <input type="checkbox"/> No <b><i>If you selected “Yes,” you should not be a subject for this experiment and you should stop right now. Otherwise, please continue...</i></b></p>
<p>2. Have you ever experienced dizzy spells? <input type="checkbox"/> Yes <input type="checkbox"/> No If “Yes,” could you please describe these experiences?</p>
<p>3. Have you ever experienced motion sickness? <input type="checkbox"/> Yes <input type="checkbox"/> No If “Yes,” could you please describe these experienced?</p>
<p>4. Do you have normal peripheral vision? <input type="checkbox"/> Yes <input type="checkbox"/> No</p>

5. Do you have normal depth perception? <input type="checkbox"/> Yes <input type="checkbox"/> No
6. Do you need corrective lenses? <input type="checkbox"/> Yes <input type="checkbox"/> No
7. Is your eyesight corrected to 20/20 or better? <input type="checkbox"/> Yes <input type="checkbox"/> No
8. Check all that apply. I have... <input type="checkbox"/> astigmatism <input type="checkbox"/> near-sightedness <input type="checkbox"/> far-sightedness <input type="checkbox"/> color-blindness                      color(s) <input type="checkbox"/> dyslexia                                      type(s):: <input type="checkbox"/> blind spots                                      where?:
9. Do you have any hearing loss? <input type="checkbox"/> Yes <input type="checkbox"/> No If "Yes," please explain how you have/are lost/losing your hearing.
10. Do you have any balance problems? <input type="checkbox"/> Yes <input type="checkbox"/> No If "Yes," please describe the nature of your balance problem(s)?
11. Do you have a history of chronic ear infections? <input type="checkbox"/> Yes <input type="checkbox"/> No If "Yes," could you please elaborate?
12. Do you have a history of bone fractures (e.g. hip, leg, forearm, etc.)? <input type="checkbox"/> Yes <input type="checkbox"/> No If "Yes," could you please list the bones fractured and the date of the fracture?

13. Do you have any medical or orthopedic problems that cause abnormal gait patterns and may prevent you from walking fast or slow?  Yes  No

If "Yes," could you please elaborate?

14. Do you have a past or recent history of treadmill use?  Yes  No

If "Yes," when was the last time you were on a treadmill?

If "Yes," how many hours, on average, did you spend using the treadmill?

0 - 2

2 - 5

5 - 10

10+

15. Do you now or have you ever played competitive sports that involved running?

Yes  No

If "Yes," could you please list the sports?

*Previous Experience*

1. Please describe any experience you have had with Virtual Reality systems.

2. Do you play video games?  Yes  No  
If so, how often and what kind?

## APPENDIX C: Subject Instructions

### Head Mounted Display versus Desktop Monitor

This linear vection experiment investigates your matching of image motion to active locomotion. You will be walking on a treadmill while wearing a head mounted display (HMD), or viewing a flat-screen LCD monitor projecting a virtual hallway environment. The experimenter will set the treadmill speed and you will have control of the z-axis “looming” speed of the virtual hallway. Use the buttons on the gamepad to adjust the speed at which the hallway moves past you such that it feels natural for your walking speed. You will have 60 seconds per trial to match your perceptions. Be sure to keep one hand on the treadmill and manipulate the gamepad buttons with your free hand.

All trials will begin with you walking at the specified treadmill speed and the virtual hallway moving (numerically faster or slower than the treadmill speed). You are to begin adjusting the hallway speed as soon as you detect a perceptual mismatch.

To be sure you accurately matched your perceptions:

- Increase (or decrease) the hallway speed until you feel you are walking slower (or faster) than the hallway is moving
- Decrease (or increase) the hallway speed until you feel you are walking faster (or slower) than the hallway is moving
- Increase (or decrease) the hallway speed so that it feels natural for your walking speed.  
*(Therefore, requiring that you make two response reversals.)*

After seeing 60-second trial, a presence question will be shown on the screen. Presence can be defined as the “subjective experience of being on one place or environment, even when physically located or situated in another.” Answer it by depressing the buttons on the gamepad. The white bar to the right of the on-screen instructions will fill with red from the bottom as the buttons are pressed.

The on-screen presence question is as follows:

Rate your strongest sensation of presence in the virtual hallway during the last trial.

- 0: Not at all there. (all white)
- 100: Completely there. (all red)

(Be sure to disregard your sensations in previous trials and rate your sense of presence in the immediately preceding trial.)

To advance to the next screen, press the toggle button (or ask the experimenter to do so when you are ready). After depressing the toggle button, you will see a large white circle with a red circle overlaid. This is an indication of the percentage of trials completed. The red circle increases until it is the same size as the white circle, or 100% of the trials have been completed.

The white button on the gamepad is used to toggle between trials, on-screen questions, and on-screen instructions. Do not press the button until instructed or are ready to proceed to the next trial.

- Prior to the start of the experiment, you will be familiarized with the gamepad and its function, the HMD and how to adjust it, and the treadmill and the range of speeds.



## Head Mounted Display versus On-Screen Projection

This linearvection experiment investigates your matching of image motion to active locomotion. You will be walking on a treadmill while wearing a head mounted display (HMD), or viewing a large screen projection of a virtual hallway environment. The experimenter will set the treadmill speed and you will have control of the z-axis “looming” speed of the virtual hallway. Use the buttons on the gamepad to adjust the speed at which the hallway moves past you such that it feels natural for your walking speed. You will have 60 seconds per trial to match your perceptions. Be sure to keep one hand on the treadmill and manipulate the gamepad buttons with your free hand.

All trials will begin with you walking at the specified treadmill speed and the virtual hallway moving (numerically faster or slower than the treadmill speed). You are to begin adjusting the hallway speed as soon as you detect a perceptual mismatch.

To be sure you accurately matched your perceptions:

- Increase (or decrease) the hallway speed until you feel you are walking slower (or faster) than the hallway is moving
- Decrease (or increase) the hallway speed until you feel you are walking faster (or slower) than the hallway is moving
- Increase (or decrease) the hallway speed so that it feels natural for your walking speed.  
*(Therefore, requiring that you make two response reversals.)*

After seeing 60-second trial, a presence question will be shown on the screen. Presence can be defined as the “subjective experience of being on one place or environment, even when physically located or situated in another.” Answer it by depressing the buttons on the gamepad. The white bar to the right of the on-screen instructions will fill with red from the bottom as the buttons are pressed.

The on-screen presence question is as follows:

Rate your strongest sensation of presence in the virtual hallway during the last trial.

- 0: Not at all there. (all white)
- 100: Completely there. (all red)

(Be sure to disregard your sensations in previous trials and rate your sense of presence in the immediately preceding trial.)

To advance to the next screen, press the toggle button (or ask the experimenter to do so when you are ready). After depressing the toggle button, you will see a large white circle with a red circle overlaid. This is an indication of the percentage of trials completed. The red circle increases until it is the same size as the white circle, or 100% of the trials have been completed.

The white button on the gamepad is used to toggle between trials, on-screen questions, and on-screen instructions. Do not press the button until instructed or are ready to proceed to the next trial.

- Prior to the start of the experiment, you will be familiarized with the gamepad and its function, the HMD and how to adjust it, and the treadmill and the range of speeds.

## Visual and Treadmill Matching for Perceptual Equivalence

This experiment investigates the matching of image motion to your walking speed. You will be walking on a treadmill while wearing a head mounted display. In some trials, the experimenter will set the treadmill speed and you will have control of the “looming” speed (“scene speed” along the direction you are facing) of the virtual hallway. In other trials, the experimenter will set the scene speed and you will have control of the treadmill speed. You will use either the buttons on the gamepad (or the buttons on the treadmill) to adjust the speed at which the hallway moves past (or the speed you are walking) you so that the scene speed 1) feels natural for your walking speed, and 2) appears stationary relative to the unseen world beyond the hallway. You will have 60 seconds per trial to match your perceptions. Be sure to keep one hand on the treadmill and manipulate the gamepad buttons with your free hand.

All trials will begin with you walking at a specified treadmill speed and the virtual hallway moving (numerically faster or slower than the treadmill speed). You are to begin adjusting the scene speed (or treadmill speed) as soon as you detect a mismatch between the scene speed and your walking speed.

To be sure you accurately matched your perceptions:

- Increase (or decrease) the hallway speed until you feel you are walking slower (or faster) than the hallway is moving
- Decrease (or increase) the hallway speed until you feel you are walking faster (or slower) than the hallway is moving
- Increase (or decrease) the hallway speed so that it feels natural for your walking speed.
- Therefore, requiring that you make two response reversals.

*(Same procedure when you are adjusting the treadmill speed. If you feel that the initial combination of treadmill speed and scene speed feels natural, either increase or decrease (your choice) the appropriate speed (scene or treadmill) and continue with the response reversal procedure.)*

After seeing 60-second trial, you will be asked to report your vection (apparent self-motion) magnitude. You will be reporting on a ratio scale. The first trial will be your “modulus,” and will assign this apparent speed of self-motion a “10.” You will compare your vection in all following trials to this modulus. For example, if in a later trial you feel you are moving twice as fast as the first block of trials, you will report a “20.” If you feel you are moving half as fast, you will report a “5.” Please report your vection magnitude verbally, and the experimenter will confirm your report.

*(You may find it easier to report your vection magnitude during the trial when you are actively making scene (or treadmill) speed adjustments.)*

After reporting your vection magnitude, the next response screen will ask you to report whether or not you felt the virtual environment appeared stable relative to the outside world. This is a Yes or No question. Suggested guidelines for answering this question (an also for adjusting the scene or treadmill speed during the trial):

- Yes: The virtual environment appeared stationary relative to the unseen world beyond for my final speed setting. “I felt as though I was walking down a stationary corridor.”
- No: The virtual environment never appeared stationary relative to the unseen world beyond for my final speed setting. “I felt as though I was walking down a corridor that was moving independently of me (either too fast or too slow).”

Press the toggle button (or ask the experimenter to do so when you are ready) to advance to the last screen. After depressing the toggle button, you will see a large white circle with a red circle overlaid.

This is an indication of the percentage of trials completed. The red circle increases until it is the same size as the white circle, or 100% of the trials have been completed. Pressing the toggle button once more will advance you to the next trial.

The white button (also has tape on it) on the gamepad is used to toggle between trials, on-screen questions, and on-screen instructions. Do not press the button until instructed or are ready to proceed to the next trial.

The buttons used to increase/decrease the scene/treadmill speed are texture coded. The “hook” Velcro is for increasing and the “pile” is for decreasing.

Prior to the start of the experiment, you will be familiarized with the gamepad and its function, the HMD and how to adjust it, and the treadmill and the range of speeds.

## Effect of Kinesthetic Working Memory on Perceptual Equivalence Ratio

This experiment investigates the matching of image motion to your walking speed. You will be walking on a treadmill while wearing a head mounted display. In all trials, the experimenter will set the treadmill speed and you will have control of the “looming” speed (“scene speed” along the direction you are facing) of the virtual hallway. You will use the buttons on the gamepad to adjust the speed at which the hallway moves past you so that the scene speed 1) feels natural for your walking speed, and 2) appears stationary relative to the unseen world beyond the hallway. You will have 60 seconds per trial to match your perceptions. Be sure to keep one hand on the treadmill and manipulate the gamepad buttons with your free hand.

All trials will begin with you walking at a specified treadmill speed and the virtual hallway moving (numerically faster or slower than the treadmill speed). You are to begin adjusting the scene speed as soon as you detect a mismatch between the scene speed and your walking speed.

To be sure you accurately matched your perceptions:

- Increase (or decrease) the hallway speed until you feel you are walking slower (or faster) than the hallway is moving
- Decrease (or increase) the hallway speed until you feel you are walking faster (or slower) than the hallway is moving
- Increase (or decrease) the hallway speed so that it feels natural for your walking speed.
- Therefore, requiring that you make two response reversals.

*(If you feel that the initial combination of treadmill speed and scene speed feels natural, either increase or decrease (your choice) the scene speed and continue with the response reversal procedure.)*

The white button (also has tape on it) on the gamepad is used to toggle between trials, on-screen questions, and on-screen instructions. Do not press the button until instructed or are ready to proceed to the next trial.

The buttons used to increase/decrease the scene speed are texture coded. The “hook” Velcro is for increasing and the “pile” is for decreasing.

Prior to the start of the experiment, you will be familiarized with the gamepad and its function, the HMD and how to adjust it, and the treadmill and the range of speeds.

## APPENDIX D: Programming (Vizard v2.10) Code

```
#####  
#  
# ROOM: LINEAR VECTION, MVL Hallway  
#           Show visual scene, adjust treadmill speed to match  
#  
# Author:   Kevin Duda (duda@mit.edu)  
# Date:     2 October 2002  
# Modified: 5 February 2004  
#  
# Realistic representation of MVL Hallway  
#  
# Displays: 1 = HMD, 2 = VREX projection, 3 = LCD Monitor  
#  
# Written for Vizard v2.10  
#  
#####  
  
import vrut  
import sid  
import sys  
import string  
import math  
import time  
import copy  
import random  
  
import ipc  
ipc.setsplash(0)  
  
#viz.fov(40, 1.333) #Vizard Default FOV Setting  
viz.fov(36, 1.333) #V8 HMD  
  
viz.cursor(viz.OFF)
```

```
#####
```

```
yes = 1
```

```
no = 0
```

```
debug = 2
```

```
savedata = yes
```

```
ball_array = no
```

```
jitter = no
```

```
fog = no
```

```
z_scale = no
```

```
pointerscale = no
```

```
percentbar = no
```

```
presence_bar = yes
```

```
disp_frame = no
```

```
go = no #yes: to go through trials without SID
```

```
sidinv = -1 #for use with gamepad to bound deflection 0..1
```

```
#other gamepad is opposite
```

```
adjust_visual = yes
```

```
adjust_eyeheight = no
```

```
infinite_mv1 = yes #no = Neurolab, yes = MVL
```

```
calibrate = no #yes, no, debug
```

```
look_to_da_side = no #rotate viewpoint 90-deg to right
```

```
#looking at right wall
```

```
look_like_LCD = no #If displaying in HMD, unplug Right Eye
```

```
#make sure HMD = off
```

```

#*****

#SUBJECT 1
#subject_eyehheight = 1.65 #meters
#OUTFILE = 'data/subject_01.dat'
#SOUTFILE = 'data/speedval_subject_01.dat'
#POUTFILE = 'data/presence_subject_01.dat'

#*****

on = 1
off = 0

HMD = on
tracker = off
dof = 3 #3 or 6

if HMD == on:
    viz.go(viz.STEREO | viz.HMD)    ##for use with HMD
    print 'HMD On'
if HMD == off:
    viz.go(viz.STEREO | viz.HMD)    ##for use with LCD
    viz.ipd(0)                       ##for use with LCD
    print 'HMD Off'

if tracker == on:
    import types

    if dof == 3:
        myTracker = vrut.addsensor('intersense')
        viz.rotate(viz.BODY_ORI, 80, 0, 0)
    elif dof == 6:
        myTracker = vrut.addsensor('is600')
        myTracker.command(1)

    if type(myTracker) != types.InstanceType:
        print 'Head Tracking On'

```

```

else:
    vrut.tracker()
    myTracker.reset()

if tracker == off:
    print 'Head Tracking Off'

#####

ARGFILE    = '040325_treadmill_visual_parsimony1.ARG'

structure = 0

# Scene Translation speed in m/s
if calibrate == yes:
    speed1 = 0
    speed2 = 0
    speed3 = 0
    VECTION_DURATION = 180.0
else:
    speed0 = 0.35
    speed1 = 0.50
    speed2 = 0.70
    speed3 = 1.00
    speed4 = 1.40
    VECTION_DURATION = 60.0

if calibrate == debug:
    speed1 = 0
    speed2 = 0
    speed3 = 0
    VECTION_DURATION = 15.0

```



```

if look_to_da_side == yes:
    viz.rotate(viz.BODY_ORI, 90, 0, 0)

title = vrut.addchild('models/title.wrl', vrut.HEAD) #title card, anchored to head so always
centered.
title.translate(0, 0, 1.8)
title.appearance(vrut.TEXMIPMAP)

presence = vrut.addchild('models/presence_card.wrl', vrut.HEAD)
presence.translate(0, 0, 1.8)
presence.appearance(vrut.TEXMIPMAP)
presence.curtain(vrut.CLOSE)

peak_vection = vrut.addchild('models/peak_vection_card.wrl', vrut.HEAD)
peak_vection.translate(0, 0, 1.8)
peak_vection.appearance(vrut.TEXMIPMAP)
peak_vection.curtain(vrut.CLOSE)

treadmill = vrut.addchild('models/treadmill_card.wrl', vrut.HEAD)
treadmill.translate(0, 0, 1.8)
treadmill.appearance(vrut.TEXMIPMAP)
treadmill.curtain(vrut.CLOSE)

all_done = vrut.addchild('models/all_done.wrl', vrut.HEAD)
all_done.translate(0, 0, 1.8)
all_done.appearance(vrut.TEXMIPMAP)
all_done.curtain(vrut.CLOSE)

daball = viz.addchild('models/ball.wrl')

```

```

#Percent done pausecard stuff:
wCircle=vrut.addchild('models/circle.wrl', vrut.HEAD)
rCircle=vrut.addchild('models/circle.wrl', vrut.HEAD)
red=vrut.addtexture('textures/Red.jpg')

rCircle.texture(red, 'Cylinder01')

initc = 0.15

wCircle.scale(initc,initc,initc)
rCircle.scale(initc,initc,initc)

wCircle.translate(0, 0, 10)
rCircle.translate(0, 0, 9.9)

wCircle.curtain(vrut.CLOSE)
rCircle.curtain(vrut.CLOSE)

def pausedot_on():
    wCircle.curtain(vrut.OPEN)
    rCircle.curtain(vrut.OPEN)
def pausedot_off():
    wCircle.curtain(vrut.CLOSE)
    rCircle.curtain(vrut.CLOSE)
def percentinc(percent):
    rCircle.scale(initc*percent, initc*percent, 1)

pausedot_off()

```

```
if infinite_mv1 == no:
    room = vrut.addchild('models/e3_corridor.wrl')
    room.scale(1.33, 1.25, 1.0)
    room.curtain(vrut.CLOSE)
    room.appearance(vrut.TEXTMIPMAP)
elif infinite_mv1 == yes:
    room1 = viz.addchild('models/mv1_no_end_doors.wrl')
    room2 = room1.clone()
    room3 = room1.clone()
    room4 = room1.clone()
    room5 = room1.clone()
    room6 = room1.clone()
    room7 = room1.clone()
    room8 = room1.clone()

    room1.curtain(viz.CLOSE)
    room2.curtain(viz.CLOSE)
    room3.curtain(viz.CLOSE)
    room4.curtain(viz.CLOSE)
    room5.curtain(viz.CLOSE)
    room6.curtain(viz.CLOSE)
    room7.curtain(viz.CLOSE)
    room8.curtain(viz.CLOSE)

    room1.appearance(viz.TEXTMIPMAP)
    room2.appearance(viz.TEXTMIPMAP)
    room3.appearance(viz.TEXTMIPMAP)
    room4.appearance(viz.TEXTMIPMAP)
    room5.appearance(viz.TEXTMIPMAP)
    room6.appearance(viz.TEXTMIPMAP)
    room7.appearance(viz.TEXTMIPMAP)
    room8.appearance(viz.TEXTMIPMAP)
```

```

if look_like_LCD == yes:
    cutout = viz.addchild('models/cutout.wrl')
    cutout.translate(0, 1.87, 1.5)
    cutout.scale(0.6, 0.5, 1.0)
    cutout.curtain(viz.CLOSE)

frame = vrut.addchild('models/e3_frame.wrl')
frame.translate(0, 1.8, 0.5)
frame.scale(0.4, 0.40, 0.40)
frame.curtain(vrut.CLOSE)

if pointerscale == yes:
    p_x = -0.08 #-0.18
    p_y = -0.056
    p_z = 1.25

    s_x = -0.15
    s_z = 1.25

    pointer = vrut.addchild('models/pointer.wrl')
    pointer.translate(p_x, p_y, p_z)
    pointer.scale(0.0125, 0.0125, 0.0025)
    pointer.curtain(vrut.CLOSE)

    scale1 = vrut.addchild('models/scale.wrl')
    scale1.translate(s_x, 0.125, s_z)
    scale1.scale(0.0035, 0.0015, 0.0005)
    scale1.curtain(vrut.CLOSE)
    scale2 = vrut.addchild('models/scale.wrl')
    scale2.translate(s_x, -0.05, s_z)
    scale2.scale(0.0035, 0.0015, 0.0005)
    scale2.curtain(vrut.CLOSE)
    scale3 = vrut.addchild('models/scale.wrl')
    scale3.translate(s_x, 0.0375, s_z)
    scale3.scale(0.003, 0.001, 0.0005)
    scale3.curtain(vrut.CLOSE)

```

```

if percentbar == yes or presence_bar == yes:
    w_x = 0.02
    w_y = -0.126 + 1.75
    w_z = 1.25 + 1.0

    r_x = 0.02
    r_y = -0.126 + 1.75
    r_z = 1.25 + 0.99

    whitebar = vrut.addchild('models/whitebar.wrl')
    whitebar.scale(0.031, 0.0255, 0.001)
    whitebar.translate(w_x, w_y, w_z)
    whitebar.curtain(vrut.CLOSE)

    whitebar25 = vrut.addchild('models/blackbar.wrl')
    whitebar25.scale(0.03, 0.0003, 0.001)
    whitebar25.translate(w_x + 0.001, w_y + 0.1375/1.5, w_z - 0.02)
    whitebar25.curtain(vrut.CLOSE)

    whitebar50 = vrut.addchild('models/blackbar.wrl')
    whitebar50.scale(0.03, 0.00045, 0.001)
    whitebar50.translate(w_x + 0.001, w_y + 0.1375, w_z - 0.02)
    whitebar50.curtain(vrut.CLOSE)

    whitebar75 = vrut.addchild('models/blackbar.wrl')
    whitebar75.scale(0.03, 0.00045, 0.001)
    whitebar75.translate(w_x + 0.001, w_y + 0.1375*1.35, w_z - 0.02)
    whitebar75.curtain(vrut.CLOSE)

    redbar = vrut.addchild('models/redrod.wrl')
    redbar.scale(0.031, 0.0255, 0.001)
    redbar.translate(r_x, r_y, r_z)
    redbar.curtain(vrut.CLOSE)

```

```

if ball_array == yes:
    balls = viz.addchild('models/ball_array.wrl')
    balls.translate(0, 1.75, 0)
    balls.curtain(viz.CLOSE)

    balls1 = balls.clone()
    balls1.translate(0, 1.75, 32.5)
    balls1.curtain(viz.CLOSE)

    balls2 = balls.clone()
    balls2.translate(0, 1.75, 64.5)
    balls2.curtain(viz.CLOSE)

#####
def PrepareNextTrial():

    global firstTime, TrialSpeedSeq, transSpeed
    global trialNum, duration, numberOfTrials
    global TreadSpeedMPH, TrialStartSpeed, TrialNumArray

    try:
        firstTime
    except NameError:
        firstTime = 0
        trialNum = 0
        file = open(ARGFILE, 'r')

        TrialNumArray = []
        TreadSpeedMPH = []
        TrialStartSpeed = []

        #read in speed sequence for trials

```

```

all = file.readlines()

for line in all:
    s = string.split(line)
    TrialNumArray.append(s[0])
    TreadSpeedMPH.append(s[1])
    TrialStartSpeed.append(s[2])

file.close()

numberofTrials=len(TrialNumArray)

trialNum = trialNum + 1

if trialNum <= len(TrialNumArray):
    duration = VECTION_DURATION

    if TreadSpeedMPH[trialNum-1] == '1.1':
        if TrialStartSpeed[trialNum-1] == '0':
            transSpeed = 0.5*0.25 #25% of m/s
        elif TrialStartSpeed[trialNum-1] == '1':
            transSpeed = 0.5*1.75 #175% of m/s

    elif TreadSpeedMPH[trialNum-1] == '1.6':
        if TrialStartSpeed[trialNum-1] == '0':
            transSpeed = 0.7*0.25
        elif TrialStartSpeed[trialNum-1] == '1':
            transSpeed = 0.7*1.75

    elif TreadSpeedMPH[trialNum-1] == '2.2':
        if TrialStartSpeed[trialNum-1] == '0':
            transSpeed = 1.0*0.5
        elif TrialStartSpeed[trialNum-1] == '1':
            transSpeed = 1.0*1.5
        elif TrialStartSpeed[trialNum-1] == '2':
            transSpeed = 1.0

```

```

elif TreadSpeedMPH[trialNum-1] == '3.1':
    if TrialStartSpeed[trialNum-1] == '0':
        transSpeed = 1.4*0.25
    elif TrialStartSpeed[trialNum-1] == '1':
        transSpeed = 1.4*1.75

print 'Trial No.', trialNum
print TreadSpeedMPH[trialNum-1]

vrut.callback(vrut.TIMER_EVENT, 'RunTrial')
vrut.starttimer(START_TRIAL)

else:
    vrut.starttimer(END_CARD)

#####
ofile = open(OUTFILE, 'w')
sofile = open(SOUTFILE, 'w')
pofile = open(POUTFILE, 'w')

def SaveTrialData(mode, data=[]):
# Saves the trial data. Writes information about the trial also.
# 'setup': writes headers to file
# 'write': writes raw sid data to file
# 'close': closes file

    global ofile, pofile
    global ydisp, trialNum, transSpeed, presence_val, speed_val

    if mode == 'setup':
        output = 'Time(s)' + '\t' + 'Scene_V(m/s)' + '\t' + 'Trial#' + '\n'
        ofile.write(output)
        ofile.flush()

```



```

elif mode == 'setup_speed_presence':
    speed_output = 'Trial#' + '\t' + 'Scene_V(m/s)' + '\n'
    sofile.write(speed_output)
    sofile.flush()

    presence_output = 'Trial#' + '\t' + 'Presence' + '\n'
    pofile.write(presence_output)
    pofile.flush()

elif mode == 'write':
    output = str(t3 - t1) + '\t' + str(transSpeed) + '\t' + str(trialNum) + '\n'
    ofile.write(output)
    ofile.flush()

elif mode == 'write_speed_summary':
    speed_output = str(trialNum) + '\t' + str(speed_val) + '\n'
    sofile.write(speed_output)
    sofile.flush()

elif mode == 'write_presence':
    presence_output = str(trialNum) + '\t' + str(presence_val) + '\n'
    pofile.write(presence_output)
    pofile.flush()

elif mode == 'close':
    ofile.close()
    sofile.close()
    pofile.close()
    print 'Data Files Closed'
else:
    print 'error'

```

```
#####
```

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#####

wall_borders= [-0.62,0.62,-0.95,0.77] # left, right, bottom, top limits

def walls ():
#Sets up walls for the corridor; if viewer tries to move beyond the
#walls of the corridor, the view is bumped back into the view of the
#corridor. For use with movement/animation callback

    currentPos=vrut.get(vrut.HEAD_POS)

    if currentPos[0] < wall_borders[0]:
        vrut.translate(vrut.HEAD_POS, wall_borders[0]-currentPos[0], 0, 0)

    if currentPos[0] > wall_borders[1]:
        vrut.translate(vrut.HEAD_POS, wall_borders[1]-currentPos[0], 0, 0)

    if currentPos[1] < wall_borders[2]:
        vrut.translate(vrut.HEAD_POS, 0, wall_borders[2]-currentPos[1], 0)

    if currentPos[1] > wall_borders[3]:
        vrut.translate(vrut.HEAD_POS, 0, wall_borders[3]-currentPos[1], 0)
```

```

#####
START_TRIAL = 1
SHOW_ROOM = 2
MOVE_ROOM = 3
PRESENCE = 4
PEAK_VECTION = 5
TREADMILL_CHANGE = 6
PAUSE_CARD = 7
END_TRIAL = 8

zeroy = sid.get()[1]

if savedata == yes:
    SaveTrialData('setup_speed_presence')

def RunTrial(num):
    global distance, distancel
    global t1, t2, t3, duration, ydisp, yydisp
    global orientation_data
    global position_x, position_y, position_z
    global omega_x, omega_y, omega_z
    global unknown_channel
    global transSpeed
    global eyeht
    global speed_val, presence_val
    global mywindow, mywindow1, mywindow2, mywindow3, mywindow4

    if num == START_TRIAL:
        trial_startTime = time.time() #time at which current trial starts
        distance = 0.0
        distancel = 0.0
        yydisp = 0.0

        if tracker == on:
            myTracker.reset()

```

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    if savedata == yes:
        SaveTrialData('setup')
    viz.starttimer(SHOW_ROOM)

elif num == SHOW_ROOM:
    if infinite_mv1 == no:
        room.curtain(viz.OPEN)
        viz.eyeheight(1.7 + subject_eyeheight)
    elif infinite_mv1 == yes:
        viz.eyeheight(0.2 + subject_eyeheight)
        room1.curtain(viz.OPEN)
        room2.curtain(viz.OPEN)
        room3.curtain(viz.OPEN)
        room4.curtain(viz.OPEN)
        room5.curtain(viz.OPEN)
        room6.curtain(viz.OPEN)
        room7.curtain(viz.OPEN)
        room8.curtain(viz.OPEN)

    if look_like_LCD == yes:
        cutout.curtain(viz.OPEN)

        #####
        mywindow = viz.add(viz.WINDOW)
        view = viz.add(viz.VIEWPOINT)
        view.translate(0, subject_eyeheight, 1.5)
        mywindow.viewpoint(view)

        mywindow.visible(viz.ON)
        mywindow.position(0.124, 0.775)
        mywindow.size(0.25, 0.545)
        mywindow.fov(38, 0.625)

```

```

if ball_array == yes:
    balls.curtain(viz.OPEN)
    balls1.curtain(viz.OPEN)
    balls2.curtain(viz.OPEN)

pausedot_off()

if fog == yes:
    viz.clearcolor(0.65, 0.65, 0.65)
    viz.fogcolor(0.65, 0.65, 0.65)
    viz.fog(0.1750)

if adjust_eyehight == yes:
    eyeht = 1.5

if disp_frame == yes:
    frame.curtain(vrut.OPEN)

ydisp = 0

if pointerscale == yes:
    pointer.curtain(vrut.OPEN)
    scale1.curtain(vrut.OPEN)
    scale2.curtain(vrut.OPEN)
    scale3.curtain(vrut.OPEN)

if percentbar == yes:
    whitebar.curtain(viz.OPEN)
    whitebar25.curtain(viz.OPEN)
    whitebar50.curtain(viz.OPEN)
    whitebar75.curtain(viz.OPEN)
    redbar.curtain(viz.OPEN)

t1 = t2 = time.time()

```

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viz.starttimer(MOVE_ROOM)

elif num == MOVE_ROOM:
    t3 = time.time()

    if tracker == on:
        if dof == 3:
            orientation_data = myTracker.get()
            position_x = 99
            position_y = 99
            position_z = 99
            omega_x = orientation_data[3]
            omega_y = orientation_data[4]
            omega_z = orientation_data[5]
            unknown_channel = 99
            #print omega_x, omega_y, omega_z
        elif dof == 6:
            orientation_data = myTracker.get()
            position_x = orientation_data[0]
            position_y = orientation_data[1]
            position_z = orientation_data[2]
            omega_x = orientation_data[3]
            omega_y = orientation_data[4]
            omega_z = orientation_data[5]
            unknown_channel = orientation_data[6]
            #print position_x, position_y, position_z, omega_x, omega_y, omega_z
            #print orientation_data[6]

    if savedata == yes:
        SaveTrialData('write')

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if t3 - t1 < duration:

    distance = distance + transSpeed * (t3 - t2)

    if infinite_mv1 == no:
        #room.translate(0, 0.65, -distance) #Neurolab Hallway model
        room.translate(0, 1.8, -distance)      #MVL Hallway model
    elif infinite_mv1 == yes:
        if z_scale == no:
            room1.translate(0, 1.8, -distance) #MVL
            room2.translate(0, 1.8, -distance + 32.50)
            room3.translate(0, 1.8, -distance + 64.50)
            room4.translate(0, 1.8, -distance + 96.50)
            room5.translate(0, 1.8, -distance + 128.5)
            room6.translate(0, 1.8, -distance + 160.5)
            room7.translate(0, 1.8, -distance + 192.5)
            room8.translate(0, 1.8, -distance + 224.5)
        elif z_scale == yes:
            room1.scale(1.0, 1.0, 0.8)
            room2.scale(1.0, 1.0, 0.8)
            room3.scale(1.0, 1.0, 0.8)
            room4.scale(1.0, 1.0, 0.8)
            room5.scale(1.0, 1.0, 0.8)
            room6.scale(1.0, 1.0, 0.8)
            room7.scale(1.0, 1.0, 0.8)
            room8.scale(1.0, 1.0, 0.8)

            room1.translate(0, 1.8, -distance) #MVL
            room2.translate(0, 1.8, -distance + 32.50*0.80)
            room3.translate(0, 1.8, -distance + 64.50*0.80)
            room4.translate(0, 1.8, -distance + 96.50*0.80)
            room5.translate(0, 1.8, -distance + 128.5*0.80)
            room6.translate(0, 1.8, -distance + 160.5*0.80)
            room7.translate(0, 1.8, -distance + 192.8*0.80)
            room8.translate(0, 1.8, -distance + 224.5*0.80)

```

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if ball_array == yes:
    balls.translate(0, 1.75, -distance)
    balls1.translate(0, 1.75, -distance + 32.5)
    balls2.translate(0, 1.75, -distance + 64.5)

if adjust_visual == yes:
    but = sid.buttons()
    if but == 4:
        transSpeed = transSpeed + 0.01
    elif but == 32:
        transSpeed = transSpeed - 0.01
        if transSpeed < 0.0:
            transSpeed = 0.0

if adjust_eyeheight == yes:
    but = sid.buttons()
    if but == 2:
        eyeht = eyeht + 0.01
        viz.eyeheight(eyeht)
    elif but == 16:
        eyeht = eyeht - 0.01
        viz.eyeheight(eyeht)

t2 = t3

ydisp = sidinv*sid.get()[1]
if ydisp < 0.0083:
    ydisp = 0
if ydisp > 1.0:
    ydisp = 1.0

if pointerscale == yes:
    pointer.translate(p_x, p_y + 0.175*ydisp, p_z)

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if percentbar == yes:
    redbar.scale(0.031, 0.0255*ydisp, 0.001)
    redbar.translate(r_x, r_y + 0.04 - 0.04*ydisp , r_z)

viz.starttimer(MOVE_ROOM, 0.0001)

else:

    if infinite_mv1 == no:
        room.curtain(vrut.CLOSE)
        speed_val = transSpeed
        print 'Speed =', speed_val

        SaveTrialData('write_speed_summary')
    elif infinite_mv1 == yes:
        speed_val = transSpeed
        print 'Speed =', speed_val
        SaveTrialData('write_speed_summary')
        room1.curtain(viz.CLOSE)
        room2.curtain(viz.CLOSE)
        room3.curtain(viz.CLOSE)
        room4.curtain(viz.CLOSE)
        room5.curtain(viz.CLOSE)
        room6.curtain(viz.CLOSE)
        room7.curtain(viz.CLOSE)
        room8.curtain(viz.CLOSE)

    if ball_array == yes:
        balls.curtain(viz.CLOSE)
        balls1.curtain(viz.CLOSE)
        balls2.curtain(viz.CLOSE)

frame.curtain(vrut.CLOSE)

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```
    if pointerscale == yes:
        pointer.curtain(vrut.CLOSE)
        scale1.curtain(vrut.CLOSE)
        scale2.curtain(vrut.CLOSE)
        scale3.curtain(vrut.CLOSE)

    if percentbar == yes:
        whitebar.curtain(vrut.CLOSE)
        whitebar25.curtain(vrut.CLOSE)
        whitebar50.curtain(vrut.CLOSE)
        whitebar75.curtain(vrut.CLOSE)
        redbar.curtain(vrut.CLOSE)

    if look_like_LCD == yes:
        cutout.curtain(viz.CLOSE)

        mywindow.visible(viz.OFF)
        mywindow1.visible(viz.OFF)
        mywindow2.visible(viz.OFF)
        mywindow3.visible(viz.OFF)
        mywindow4.visible(viz.OFF)

    viz.starttimer(PRESENCE)

elif num == PRESENCE:
    presence.curtain(viz.OPEN)

    if presence_bar == yes:
        whitebar.curtain(viz.OPEN)
        whitebar25.curtain(viz.OPEN)
        whitebar50.curtain(viz.OPEN)
        whitebar75.curtain(viz.OPEN)
        redbar.curtain(viz.OPEN)
```

```

pw_x = 0.1 + 0.6
pw_y = -0.126 + 1.87 + 0.01 - 0.4
pw_z = 1.7

pr_x = 0.096 + 0.6
pr_y = -0.126 + 1.8735 + 0.01 - 0.4
pr_z = 1.69

whitebar.scale(0.15, 0.1, 0.001)
whitebar25.scale(0.15, 0.0015, 0.001)
whitebar50.scale(0.15, 0.0015, 0.001)
whitebar75.scale(0.15, 0.0015, 0.001)

whitebar.translate(pw_x, pw_y, pw_z)
whitebar25.translate(pw_x - 0.008, pw_y + 0.1375/1.5 + 0.25, pw_z - 0.02)
whitebar50.translate(pw_x - 0.008, pw_y + 0.1375 + 0.4, pw_z - 0.02)
whitebar75.translate(pw_x - 0.008, pw_y + 0.1375/1.5 + 0.65, pw_z - 0.02)

but = sid.buttons()
if but == 4:
    yydisp = yydisp + 0.01
    if yydisp > 1.0:
        yydisp = 1.0
elif but == 32:
    yydisp = yydisp - 0.01
    if yydisp < 0.0:
        yydisp = 0.0

redbar.scale(0.15, 0.1*yydisp, 0.001)
redbar.translate(pr_x, pr_y + 0.155 - 0.16*yydisp , pr_z)

```

```

if go == yes:
    if trialNum == 4:
        viz.starttimer(TREADMILL_CHANGE)
    elif trialNum == 8:
        viz.starttimer(TREADMILL_CHANGE)
    else:
        viz.starttimer(PAUSE_CARD, 2.5)

elif sid.trigger():
    presence_val = yydisp
    print 'Presence =', presence_val

    SaveTrialData('write_presence')

    if trialNum == 4:
        viz.starttimer(TREADMILL_CHANGE)
    elif trialNum == 8:
        viz.starttimer(TREADMILL_CHANGE)
    else:
        viz.starttimer(PAUSE_CARD)
else:
    vrut.starttimer(PRESENCE)

elif num == PEAK_VECTION:
    presence.curtain(viz.CLOSE)
    peak_vection.curtain(viz.OPEN)

if go == yes:
    if trialNum == 12:
        viz.starttimer(TREADMILL_CHANGE)
    elif trialNum == 21:
        viz.starttimer(TREADMILL_CHANGE)
    elif trialNum == 30:
        viz.starttimer(TREADMILL_CHANGE)
    else:
        viz.starttimer(PAUSE_CARD, 2.5)

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elif sid.trigger():
    if trialNum == 5: #12
        viz.starttimer(TREADMILL_CHANGE)
    elif trialNum == 21:
        viz.starttimer(TREADMILL_CHANGE)
    elif trialNum == 30:
        viz.starttimer(TREADMILL_CHANGE)
    else:
        viz.starttimer(PAUSE_CARD)
else:
    vrut.starttimer(PEAK_VECTION)

elif num == TREADMILL_CHANGE:
    presence.curtain(viz.CLOSE)
    peak_vection.curtain(viz.CLOSE)
    treadmill.curtain(viz.OPEN)

if presence_bar == yes:
    whitebar.curtain(viz.CLOSE)
    whitebar25.curtain(viz.CLOSE)
    whitebar50.curtain(viz.CLOSE)
    whitebar75.curtain(viz.CLOSE)
    redbar.curtain(viz.CLOSE)

if go == yes:
    viz.starttimer(PAUSE_CARD, 1)
elif sid.trigger():
    viz.starttimer(PAUSE_CARD)
else:
    viz.starttimer(TREADMILL_CHANGE)

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```

elif num == PAUSE_CARD:
    peak_vection.curtain(viz.CLOSE)
    treadmill.curtain(viz.CLOSE)
    presence.curtain(viz.CLOSE)

    if presence_bar == yes:
        whitebar.curtain(viz.CLOSE)
        whitebar25.curtain(viz.CLOSE)
        whitebar50.curtain(viz.CLOSE)
        whitebar75.curtain(viz.CLOSE)
        redbar.curtain(viz.CLOSE)

    if trialNum == len(TrialNumArray):
        all_done.curtain(viz.OPEN)
        pausedot_off()
    else:
        percent = float(trialNum)/float(numberofTrials)
        percentinc(percent)
        pausedot_on()

    if go == yes:
        if trialNum == len(TrialNumArray):
            SaveTrialData('close')
        else:
            pausedot_off()
            vrut.callback(vrut.TIMER_EVENT, 'HandleTimer')
            vrut.starttimer(NEXT_TRIAL, 2)
    elif sid.trigger():
        if trialNum == len(TrialNumArray):
            SaveTrialData('close')
        else:
            pausedot_off()
            vrut.callback(vrut.TIMER_EVENT, 'HandleTimer')
            vrut.starttimer(NEXT_TRIAL)

```

```

        else:
            vrut.starttimer(PAUSE_CARD)

elif num == END_TRIAL:
    pausedot_off()
    room.curtain(vrut.CLOSE)
    vrut.callback(vrut.TIMER_EVENT, 'HandleTimer')

#####
INITIALIZE_EXP    = 1
TITLE_SCREEN     = 2
NEXT_TRIAL       = 3
SAVE_DATA        = 4
END_CARD         = 5
END_EXP          = 6

def HandleTimer(num):

    if num == INITIALIZE_EXP:
        # Setup experiment
        print 'Setting up experiment'
        vrut.starttimer(TITLE_SCREEN)

    elif num == TITLE_SCREEN:
        if go == yes:
            vrut.starttimer(NEXT_TRIAL)
            title.curtain(vrut.CLOSE)
        elif sid.trigger():
            vrut.starttimer(NEXT_TRIAL)
            title.curtain(vrut.CLOSE)
        else:
            vrut.starttimer(TITLE_SCREEN)

```

```

elif num == NEXT_TRIAL:
    PrepareNextTrial()

elif num == SAVE_DATA:
    SaveTrialData()
    vrut.starttimer(NEXT_TRIAL)

elif num == END_CARD:
    if go == yes:
        all_done.curtain(viz.OPEN)
        title.curtain(vrut.CLOSE)
        vrut.starttimer(END_EXP)
    elif sid.trigger():
        all_done.curtain(viz.OPEN)
        title.curtain(vrut.CLOSE)
        vrut.starttimer(END_EXP)
    else:
        vrut.starttimer(END_CARD)

elif num == END_EXP:
    if savedata == yes:
        SaveTrialData('close')
    print "That's all folks"
    vrut.quit()

```

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```

deltax = 0.0
deltay = 0.0
deltaz = 0.0
def myKeyboard(key):
    global deltax, deltay, deltaz
    transSpeed = 0.0
    print deltay
    if key == ' ':

```



```

    myTracker.reset()
    print myTracker.get()[3]

elif key == 'b':
    head_yaw = myTracker.get()[3]
    head_pitch = myTracker.get()[4]
    head_roll = myTracker.get()[5]
    viz.rotate(viz.BODY_ORI, head_yaw, head_roll, head_pitch) #yaw, roll, pitch
elif key == 'z':
    viz.rotate(viz.BODY_ORI, 115+180, 0, 0)
elif key == 'r':
    vrut.rotate(vrut.BODY_ORI, 90, 0, 0)
elif key == 'i':
    myTracker.command(6) #reset IS600 station
elif key == 't':
    print 'Yaw:', myTracker.get()[3]
    print 'Pitch:', myTracker.get()[4]
    print 'Roll:', myTracker.get()[5]
elif key == '8':
    deltay = deltay + 0.025
    daball.translate(deltax, deltay, deltaz)
elif key == '2':
    deltay = deltay - 0.025
    daball.translate(deltax, deltay, deltaz)
elif key == '6':
    deltax = deltax + 0.05
    viz.rotate(viz.BODY_ORI, 0.5, 0, 0)
elif key == '4':
    deltax = deltax - 0.05
    viz.rotate(viz.BODY_ORI, -0.5, 0, 0)
elif key == '5':
    deltaz = deltaz + 0.025
    daball.translate(deltax, deltay, deltaz)
elif key == '0':
    deltaz = deltaz - 0.025
    daball.translate(deltax, deltay, deltaz)

```

```
elif key == '65362':  
    transSpeed = transSpeed + 0.1
```

```
#####  
#####
```

```
vrut.callback(vrut.TIMER_EVENT, 'HandleTimer')  
vrut.callback(vrut.KEYBOARD_EVENT, 'myKeyboard')  
vrut.starttimer(INITIALIZE_EXP, 0.5)
```