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Motion sickness and proprioceptive aftereffects following virtual environment exposure

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Abstract

To study the potential aftereffects of virtual environments (VE), tests of visually guided behavior and felt limb position (pointing with eyes open and closed) along with self-reports of motion sickness-like discomfort were administered before and after 30 min exposure of 34 subjects. When post- discomfort was compared to a pre-baseline, the participants reported more sickness afterward ($p < 0.03$). The change in felt limb position resulted in subjects pointing higher ($p < 0.038$) and slightly to the left, although the latter difference was not statistically significant ($p = 0.08$). When findings from a second study using a different VE system were compared, they essentially replicated the results of the first study with higher sickness afterward ($p < 0.001$) and post- pointing errors were also up ($p < 0.001$) and to the left ($p < 0.001$). While alternative explanations (e.g. learning, fatigue, boredom, habituation, etc.) of these outcomes cannot be ruled out, the consistency of the post- effects on felt limb position changes in the two VE implies that these recalibrations may linger once interaction with the VE has concluded, rendering users potentially physiologically maladapted for the real world when they return. This suggests there may be safety concerns following VE exposures until pre-exposure functioning has been regained. The results of this study emphasize the need for developing and using objective measures of post-VE exposure aftereffects in order to systematically determine under what conditions these effects may occur.

1. Introduction

Varying degrees of motion sickness-like symptoms have been reported in nearly every flight simulator fielded by the military services (Kennedy *et al*, 1989). Similar symptoms, sometimes known as cybersickness, are now being reported with increasing regularity by users of virtual environment (VE) devices (Kennedy *et al*, 1995) and the problem seems even greater for VE devices. In flight simulators 60–70% of pilots reported susceptibility (Kennedy *et al*, 1993a), while in VE studies (Kennedy *et al*, 1996b), 90–95% of the participants report experiencing symptoms. Furthermore, based on observations in our laboratory the effects do not cease immediately upon post-exposure, but linger on, leaving those who are most affected feeling unsteady or disoriented or sick. The goal of the present research was to assess these potential aftereffects.

Past research has established the use of postural stability measures (Kennedy and Stanney, 1996; Cobb, 1999) and self-report questionnaires (Kolasinski, 1996; Stanney and Hash, 1998) for assessing aftereffects from VE exposure; however, few efforts have attempted to use measurements of proprioception in this capacity (see Rolland *et al*, (1995) for a notable exception). Static and dynamic position of the fingers and limbs can be used to index the status of the proprioceptive or kinesthetic senses (Cordo and Harnad, 1994; Kandell *et al*, 1995). Touch and proprioception allow a person to sense with their hands the size, shape, and position of objects. In addition, Gibson (1966) has suggested that coordinated locomotion throughout an environment is a result of a learned correlation between the optic flow that indicates self-motion and proprioceptive feedback. When in a VE, a person will use their proprioceptive senses to operate the haptic interface (e.g. glove), joystick, mouse, or other device that moves them about the virtual world. Based on observations in our laboratory, when a person initially interacts with a VE their movements are relatively jerky and

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uncoordinated. James and Caird (1995) attributed this difficulty to a lack of correlation between the visual scene provided by the HMD and the haptic experience. As people *adapt* and *rescale* their movements to those which are required to effectively manipulate the VE, however, their behaviors become more fluid and controlled. We believe that the initial uncoordinated movements are similar to those seen in the early studies of perception that used perceptual rearrangements (e.g. Helmholtz, 1925). In these studies, the visual field was laterally displaced 17° through the use of wedge prisms. When a person initially looked at an object through the prism they would predictably go to where it appeared to be and err in the direction of the displacement (just as VE users go to where virtual objects appear to be through the helmet-mounted display (HMD) with its optical distortions). With practice in using the prisms, however, perceptions are rescaled and these errors were overcome (just as VE users become more fluid in their movements over time). More importantly, once the prisms were removed, errors (post effects) occurred in reaching performance, this time in the direction opposite to the prismatic displacement, and people needed a period of time after removing the prisms to readapt to normative functioning.

This adaptation or recalibration of perspective presents the question whether users of VEs experience similar aftereffects post-VE exposure and thereby require a period of time to readapt to normative functioning after leaving the virtual world? If so, is this a change in vision, vestibular function, or proprioceptive perception? To date evidence for such post-exposure aftereffects in VE is anecdotal. One researcher from our University (reported in the international press (Strauss, 1995; p. A1)) following 20 min exposure in a see-through HMD, attempted to drink a soda and found herself pouring the soft drink into her eye. Another striking example of compromising aftereffects was a child who, after playing a home-based VE game system for an extended period of time, upon post-exposure thrust a cue stick into his eye during a game of billiards (Burnett, 1996). These anecdotal episodes suggest the potential need to measure proprioception following VE exposure. If proprioceptive aftereffects are identified, then means to manage them must be initiated in order to ensure the safe use of VE technology. The overall objectives of the present effort were to systematically measure proprioception pre- and post-VE exposure and assess if any aftereffects existed, which would suggest the need for a period of time to readapt after VE exposure. Self- reports of cybersickness were also assessed for comparison.

1.1. Background

1.1.1. Cybersickness

The measurement of motion sickness signs and symptoms have been classified into three clusters: (1) nausea and vomiting; (2) oculomotor disturbances (eyestrain); and (3) disorientation, ataxia (postural stability), and vertigo (Kennedy *et al*, 1993b). Virtual environment systems produce more disorientation and nausea than oculomotor-related symptoms (Kennedy and Stanney, 1997). Aftereffects from exposure to simulator systems, the ancestors of emerging VE systems, have been known to persist for several hours after exposure ceases (Baltzley *et al*, 1989; Ungs, 1987), particularly if the exposures are lengthy (Crosby and Kennedy, 1982). These aftereffects include reports from hundreds of flight simulator experiences, of illusory climbing and turning sensations, perceived inversions of the visual field, and reduced motor control (Baltzley *et al*, 1989). Other problems include reduction of complex psychomotor flexibility (Lampton *et al*, 1994), asthenopia (Ebenholtz, 1988), changes in accommodation and vergence (Rushton *et al*, 1994), suggestion of a disturbed vestibulo-ocular reflex (VOR) function (Hettinger *et al*, 1987), and increased risk in adverse adaptations to subsequent normal environments (Regan and Price, 1994). Relatedly, all of these effects have also been documented subsequent to long-term exposure to microgravity in space (Bock, 1996; Reschke *et al*, 1994a; Reschke *et al*, 1994b; Paloski *et al*, 1992; Watt, 1997). We hypothesize that similar aftereffects may be an issue with VE systems. The concern is that, as with post-effects of space flight, if such aftereffects are experienced with VE systems these physiological changes may make individuals maladapted for their return to the ‘real’ world once VE interaction concludes.

The works of Chien and Jenkins (1994) and Kennedy *et al* (1990) involving simulator sickness, and Durlach and Mavor (1995) and Kalawsky (1993) involving cybersickness, can be consulted to note the importance of these motion sickness symptoms and potential transfer of inappropriate sensory-motor compensations to the real-world post system exposure. They suggest several measures of VE aftereffects, including motion sickness, postural stability; and physiological responses (e.g. heart rate, blood pressure, muscle tension, galvanic skin response, electroencephalogram, electrocardiogram, etc.). A few simulator and VE studies even mention in passing the plastic nature of proprioception (Kennedy *et al*, 1990; Kalawsky, 1993). Few, however, have explored the possibility of objectively measuring changes in proprioception to gauge the aftereffects of VE exposure, although methods for measurement of such motor effects have been available for some time (Barany, 1906; Slinger and Horsley, 1906) and constitute a lively area in modern neuroscience (Soechting and Flanders, 1989, 1993).

When wearing helmet-mounted displays (HMD) in a virtual world there are several anomalies that could lead to measurable changes in proprioception, including visual distortions, position tracking errors, and scaling differences between the real world and the VE rendition. These changes may be particularly driven by environments where the VE training objectives require exacting hand-eye coordination. Rolland *et al* (1995) state that the 'central component[s] of medical, military, and other training systems is learning subtle, coordinated hand-eye movements' within the VE environment. If these training environments drive adaptive changes in proprioception, then post-exposure aftereffects should be measured to determine the extent of the adaptation and if it will hinder normative functioning.

1.1.2 Proprioceptive adaptation in virtual environments

To demonstrate the utility of measuring rearrangements in proprioception in order to gauge VE aftereffects it is important to determine if VE users must physiologically adapt in order to function appropriately in a virtual environment. One example was provided by Rolland *et al* (1995), who observed that participants experienced pointing errors in the *y* and *z* dimensions upon first use of a see-thru HMD. Also, they measured a 43% improvement in the speed of the performance of manual tasks when compared to baseline measures. They observed that participants' performances slowed down immediately upon entering the virtual environment, encumbered by 'short and tentative' and 'uncoordinated' movements. The participants' reaching movements were also observed as 'uncertain and inaccurate.' Wright (1995) reported that perceived position can also be altered in a virtual environment. He demonstrated that participants experienced a 59% error in the perceived dimension of forward distance, 28% for height, 50% for lateral distance, and a speed perception error of 59%. James and Caird (1995) examined the locomotion ability of individuals with no previous experience with virtual worlds. They found that the locomotion accuracy of these participants in a VE was error prone, with nearer distances being undershot while farther distances were overshot. This suggests that (p. 1409) 'initial locomotion accuracy (in a VE) is limited by the necessity of establishing a perceptual correlation between visual and haptic information' and that results from this experiment (p. 1407) 'can be interpreted as evidence for minimal calibration between proprioceptive feedback and optic flow' of the virtual world. These studies demonstrate that altered perceptual information is received by users in virtual environments. Initial errors in locomotion performance and movement control in VEs may thus potentially be attributed to the difference in visual perception of a virtual target with the proprioceptive representation of the arm and hand (Soechting and Flanders, 1989; Rolland *et al.*, 1995). Mather and Lackner (1980) hypothesized that while visual perception may change in a displaced environment, the 'proprioceptive position signals in the muscles and joints of the hand and arms remain unchanged'.

McGonigle and Flook (1978) and Mather and Lackner (1980), while conducting hand–eye coordination experiments under the conditions of visual displacement brought about by prisms, ascertained that the process of adapting to the displacement necessitates minimizing the conflict between the visual and proprioceptive stimuli. They believe that changes (adaptation) in visuo-motor performance are manifested when the real-world proprioceptive cues are matched with the visual cues presented in the altered environment. Typically, this has been shown to be accomplished via the participants' ability to sense their self-generated hand motion in addition to the visual information provided by targets (Wallace, 1978; Welch, 1969; Hay and Pick, 1966).

The inherent danger of the altered visual and proprioceptive stimuli in VEs is that, once users leave the VE and return to the real-world, their hand-eye coordination and felt limb position may be altered because of adaptation to aspects of the altered renditions of the virtual world. Rolland *et al* (1995) and Biocca and Rolland (1998) warn of, and demonstrate, such a problem with see-thru HMDs. They state that participants' perceptual systems might adapt to the VE and become 'miscalibrated for the real world'. This miscalibration could directly affect visuo-motor coordination. Their participants reported that their altered state of hand-eye coordination did complicate their real-world performance. Rolland *et al.* (1995) demonstrated that post-exposure pointing errors occurred in all three axes. In addition, McGonigle and Flook (1978) demonstrated that adaptation to altered visual cues does not simply disappear immediately after exposure. They state that many investigators assume that within twenty-four hours this adaptation has dissipated. However, they point out that squirrel monkeys have shown adaptation effects for up to 48 h after exposure (also cf. Baltzley *et al*, 1989). McGonigle and Flook (1978) also demonstrated that significant aftereffects from prismatic adaptation could be found in humans from two to four weeks after initial exposure, given repeated exposure periods. In addition, Guedry (1965) has shown neurophysiological (vestibulo-ocular reflex) changes lasting 60–90 d following protracted (12 d) exposure to slow rotation. These studies are important because they support the contention that participants do indeed adapt to new visual perceptual cues, and that this adaptation can manifest itself in the real world for extended periods of time. Taken together, these studies suggested to us that in addition to postural measures (Kennedy and Stanney, 1996) and self-reports of sickness (Kennedy *et al.*, 1993b), a measure of proprioception could be a useful adjunct to assessment of the extent of aftereffects due to VE exposure.

In order to measure effectively proprioceptive adaptation to VEs, it is essential to understand that such adaptation occurs through a process of visual-kinesthetic interactions. Pointing exercises can be used as direct assessment of these adaptive properties (Ghez, 1991). Specifically, pointing tests (PT) have provided great insight into the neural mechanisms involved in combining information from different sensory modalities (i.e. visual and proprioceptive) into a common frame of reference, and then transforming this 'synthesized' sensory information into cortical motor output maps and motor commands for arm, hand, and finger pointing to targets in three-dimensional space (Soechting and Flanders, 1989, 1993). The arm, hand, finger pointing errors in sensory conflict (e.g. prismatic studies) have been used not only to identify specific neural mechanisms involved in representing and transforming multisensory information into voluntary motor performance, but those tests have also provided insight into the so-called adaptive properties or possible 'recalibration' of proprioception (Pascual-Leone *et al*, 1994; Soechting and Flanders, 1989, 1993).

For the initial arm, hand, finger pointing movement directed to a target in extrapersonal space, information about target location is provided by visual cues, and information about the position of arms, hand, fingers, and deviations from the intended trajectory, is provided by proprioception. Under some circumstances the vestibular system, too, is involved. The transformation of this multisensory information into a common central nervous system (CNS) frame of reference represents the initial phase in the cortical motor output maps that produce patterns of voluntary movements for pointing or heading to targets in three-dimensional space. The three phases of: (1) target identification; (2) planning of action; and (3) motor execution are regulated by three distinct regions of the cerebral cortex, comprising the pre-motor areas of the frontal cortex, the posterior parietal cortex, and the primary motor cortex (Ghez, 1991).

One of the earliest PTs was Barany's (Barany, 1906; Roorda, 1925), which was originally developed to be a part of a clinical examination of so-called 'voluntary' movements in eye-hand coordination for pointing to targets involving visual and proprioceptive information in three-dimensional space. In this PT test, the patient was directed to touch the examiner's forefinger with her own, with eyes open. She was next directed to close her eyes, drop her hand and arm, bring them back to the original position, and again touch the examiner's finger, located in the original position and with eyes still closed. The test of moving the pointing finger first away, and then back to the examiner's finger, serving as 'target' in extrapersonal space, was conducted in both horizontal and vertical planes. The PT was repeated with the patient's eyes shut, thus serving as a measure of mismatches between visual and proprioceptive information in voluntary motor performance.

The purpose of the present study was to use an objective pointing test and to measure changes in proprioception and to gauge the existence, if any, of aftereffects from VE exposure and to compare these findings to self-reports of sickness in the same environment.

2. Method

2.1. Participants

Thirty-four participants, 14 females and 20 males, with an average age of 25.79 ($SD = 4.72$) years volunteered for this study. The participants first provided their informed consent and verified that they were in good health. All were undergraduate or graduate students from the University of Central Florida and received class credit for their participation. The participants had no known sensorimotor impairments that could have affected their performance on the pointing test. All reported themselves to have 20/20 (corrected) vision and were right-handed.

2.2. Apparatus

2.2.1. Pointing test device

A modern version of Barany's (1906) PT was developed for this experiment. Rather than touching the examiner's forefinger, participants had to touch a point on a digitizing pad that captured the location of the point touched. The hardware chosen for the PT data collection was a Summagraphics SummaSketch FX digitizing tablet. The tablet has a 0.3 m $\times$ 0.3 m active coordinate area. The resolution of the tablet's working area in both the X and the Y directions is 0.025 mm. A cordless stylus (pen) was chosen for the tablet's position input device. To capture the positional data, the wireless stylus was attached to a Velcro equipped elastic band that fitted snugly around the participants' index finger.

The PT device was run on a 90 MHz Pentium computer with 16 MB of RAM. In the default power-on mode, when the stylus was placed in close proximity to the tablet surface, the tablet controller sent out continuous positional data in 5 byte binary RS-232 serial information packets. This default setup was called the MM/SummaSketch Format. An interface software driver was written to capture the digitizer output and translate it into real-world coordinates.

The digitizing tablet was mounted in a vertical manner on the outer vertical side surface of a mobile printer stand. The tablet was mounted such that the center of the tablet was 0.9 m from the floor. A 6.25 mm circular target was placed in the center of the tablet under the tablet plastic overlay. This provided a two-dimensional Cartesian plane system in space.

Audible tones were designed to guide participants through the pointing exercise. A single tone was used to indicate that a participant was to touch the target in the center of the tablet. When the computer received the tablet's position data packet, a dual 'beep beep' tone was used to indicate to participants that the position data had been received. Specialized software was written to permit automated analysis of the pointing data.

2.2.2. Pointing test protocol

To examine several orientations of the pointing motion (i.e. movements in the sagittal and transverse planes), each PT experimental session was divided into center, left (30° to the left of center), and right (30° to the right of center) orientational components. Each orientational component consisted of 12 pointing trials to the target on the digitizing pad. Participants were required to sit in an armless chair in an upright position with their dorsum against the chair back during the trials. The Velcro equipped elastic band containing the stylus was then attached to the index finger of the participants' right hand. Next, participants were instructed to point with the stylus at the target on the digitizing pad, which was located in the frontal plane, while the pad was positioned at arm's length using the following procedure. The participants extended their hand to a point in space and then the tablet and stand were moved into position such that the participants could comfortably touch the surface of the tablet. Once the equipment was positioned correctly, and verified to be sending position data, PT measurements could be taken.

The instructions for the pointing test directed the participants to start and stop their pointing motions with their hand resting on their right leg. During movement, the arm was fully extended until the tip of the stylus touched the pad. The principle movement direction was forward and upward toward the target (i.e. flexion and extension of the shoulder and elbow in the sagittal plane). In the left and right orientations, movements in the transverse (i.e. horizontal) plane were also required. A visor was worn around the neck of the participants to obstruct the view of the initial position of the arm. The order of presentation of the orientations was center then left then right. When the digitizing pad was placed in the right and left orientations, participants were instructed to keep their nose orthogonal to the frontal plane.

Participants were informed that within each trial the pointing movements would be triggered by audible beeps. They were instructed to listen for a single tone (example tones were given). They were told that once they heard this tone, they were to touch the target in the center of the tablet. Participants were informed that once the computer registered their touch, a dual 'beep beep' tone would sound (example tones were given) which indicated they should return their hand to the 'rest' position.

Two types of pointing trials were alternated. Both trials began with participants looking at the target and pointing to it with eyes open. For 'eyes-open' trials participants were told to repeat this procedure, and for 'eyes-closed' trials participants were told to close their eyes and then point to the memorized target location. Three orientations were tested (left, right and center) which consisted of 6 eyes-open and 6 eyes-closed trials. 3 of these trials were with no delay between the first and second touch and 3 were with a 5-second delay (Fig.1). There were three determinations made for each orientation and each delay in which the differences between the first and second touch were averaged across the 3 trials. The delay condition was included because it was felt that the memory store of the target could be expected to decay (Card *et al*, 1983) and this might provide a more sensitive measure of proprioceptive change than immediate responses when VE exposures were studied.

In summary, there were three orientations (L, R, C), two modes (eyes open and closed), two delays (0, 5) and three determinations (1, 2, and 3) and each of these 36 observations or touches comprised the pre-test or baseline session. There was a practice session prior to the pre-test and two post-test sessions. Post-test session 1 was conducted immediately after the VE exposure and the second between 20–30 min later.

The pointing test's metric properties were evaluated by using the practice session and the pretest, with approximately 20 min between the administrations. Measurements of the pointing location in the X and Y directions were taken both with eyes-open and eyes-closed. In the eyes-open condition participants hit the target every time and showed essentially zero variances. For the eyes-closed condition only, test-retest reliability was examined between the first and second sessions. Based on the results from the individual eyes-closed trials, over orientation and delay, this condition proved to be reliable ($0.4 < r < 0.7$).

2.2.3. Helmet-mounted display

The Kaiser Electro-Optics Virtual Immersion (VIM) 500 hrpv head-mounted display (HMD) was used to display the virtual environment. It provided a 50° field of view which accepts an NTSC 2-channel stereo or 1-channel mono video signal from an VGA-NTSC converter box. The NTSC signal was projected into separate

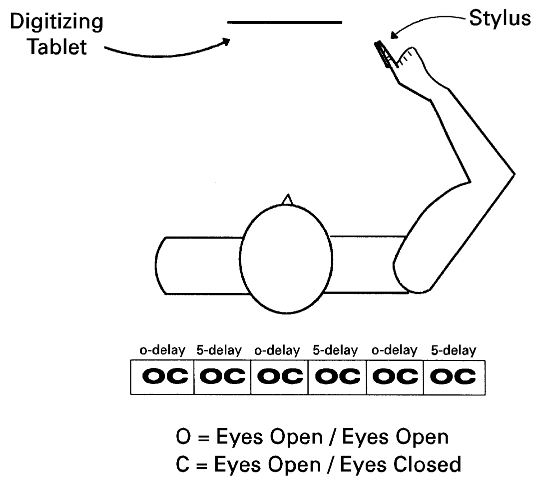

Fig. 1. Schematic view of experimental setup and pointing task protocol.

right and left color, 37.5 mm LCD screens. The HMD was operated solely in the stereoscopic mode for the duration of the experiment.

2.2.4. Virtual environment

The virtual environment (VE) was developed using WorldToolKit for Windows, Version 2.0 and was run under the Windows 95 operating system. It was designed to include many of the fundamental interactive techniques required in VEs, including complex spatial navigation and pick and placement. Several of the standardized tasks in the Virtual Environment Performance Assessment Battery developed by the US Army Research Institute in Orlando, Florida (Lampton *et al*, 1994) were incorporated into the task scenarios. The scene content was two rooms separated by a wall with a doorway. The first room had a set of 15 colored balls (orange, blue, green, white, yellow, 3 of each color) along one wall and 15 matching platforms along the opposite wall. There was a column in the center of this room. In the other room there were 6 large columns divided into two rows of three columns each. The columns were alternating colors of blue and red.

A 133 Mhz, Pentium computer with 32 MB of RAM was used to generate the virtual environment. During testing, the screen resolution was set at 640×480 pixels. All participants used a standard three button mouse to move about and manipulate objects. VGA output from the graphics card was sent to the VGA-NTSC converter box via a standard VGA connector cable which was then sent to the HMD.

2.2.5. Virtual tasks

There were two virtual tasks to be performed. The first was an object manipulation pick-and-place task similar to the Bins task used by Lampton *et al* (1994). This task required participants to move the 15 balls on the left side of the room over to the matching 15 platforms on the right side of the room. While traversing from one side of the room to the other, the participants were to move clockwise around the column in the center of the room one time before placing the ball over the matching platform.

The second was a locomotion task in the second room; participants had to perform a column circling task in which they traversed from one column to the next, again moving clockwise around each one before continuing to the next. This is similar to the Figure eight task used by Lampton *et al.* (1994).

2.2.5.1. Simulator sickness questionnaire (SSQ). In order to measure cybersickness experienced upon post-VE exposure, the participants filled out the Simulator Sickness Questionnaire (SSQ) (Kennedy *et al*, 1993b). The SSQ consists of a checklist of 26 symptoms, each of which is related in terms of degree of severity (none, slight, moderate, severe), with the highest possible total score being 235. A diagnostic scoring procedure is used to obtain a global score reflecting the overall discomfort level known as the Total Severity (TS) score. The SSQ also provides scores on three subscales which represent separable dimensions of simulator sickness (i.e. nausea, oculomotor disturbances, and disorientation).

2.2.5.2 Motion history questionnaire (MHO). The MHQ (Kennedy *et al*, 1992) was used to assess susceptibility based on past occurrences of sickness in inertial environments. This 15-item paper-and-pencil questionnaire permits an individual to list past experience in provocative motion environments and the history of their motion sickness symptom reactions. Scores on the MHQ are generally predictive of an individual's susceptibility to motion sickness.

2.2.5.3. Long-term aftereffects questionnaire. Participants were given a paper-and-pencil SSQ to take home and asked to indicate at set times (2 and 4 h post-exposure, as well as the following morning) the presence, or lack, of any adverse symptoms (Baltzley *et al*, 1989).

2.3. Procedure

Participants read and signed the informed consent form and filled out the MHQ and a baseline SSQ which was used to screen and deselect subjects who were unfit. Next, participants performed the two baseline pointing test trials that were used to establish the reliability of the pointing test. Immediately following the PT, participants remained in the chair used for the PT and were relocated in front of the computer displaying the virtual environment. The participants remained seated throughout the entire experimental session. The HMD was placed on the participant's head and adjusted (size and IPD) to fit. Participants were shown how to use the mouse to move in the VE; movements to the right, left, forward, and backward were demonstrated.

The first virtual task was demonstrated to participants, how to place the mouse pointer on a ball and then to click, thereby attaching the ball to the viewpoint, and then how to move the ball to the corresponding colored platform on the left side of the room. While traversing from one side of the room to the other, the participants were shown how to move clockwise around the column in the center of the room one time before placing the ball over the matching platform, and how to click and release the ball onto the platform. The second task, column circling, was then demonstrated. The ball pick-and-place task was then performed until all of the balls were placed on the platforms and then the column circling task until exposure time had expired.

Participants were informed that their exposure duration would be 30 min. They were instructed to terminate their VE interaction prematurely should they become severely ill or disoriented. When they commenced the first virtual task, the room lights were extinguished and remained out for the duration of the VE exposure.

After exposure, the HMD was removed and the participants, with eyes closed, were swiveled in the chair back to the PT device. The Velcro band was placed on their index fingers and the visors were placed around their necks. The lights were turned on and they were instructed to open their eyes and immediately commence the pointing test.

Immediately after completing the PT participants filled out the SSQ, twenty minutes later they performed the pointing task again and after thirty minutes the SSQ was administered again. Participants then signed an informed consent form which they had read before participating, which they agreed to abstain from driving or performing any activities requiring coordinated behavior for two hours after leaving the test site. Lastly, the participants were given the long-term aftereffects questionnaire and instructed to fill it out periodically over the course of the ensuing 24 h.

2.3.1. Data analysis

A mean of the three determinations at each orientation and for each delay was calculated separately for each participant. The mean difference between the participant's pre-exposure pointing error for each independent delay variable was subtracted from the comparable post-mean value and used as a measure of change elicited during exposure to the virtual environment. The variables included delay (none, 5-seconds), orientation (center, left, right), and direction (X and Y). This analysis was performed separately for the eyes-open and eyes-closed scenarios.

3. Results

3.1. Pre- versus post-exposure VE sickness

The mean Simulator Sickness Questionnaire (SSQ) scores for the nausea, oculomotor, and disorientation subscales and total severity score are presented in Table 1 and Fig. 2. These scores are for the pre- VE exposure, immediately post-exposure, and 30 min post-exposure measurements. The level of total symptomatology (i.e. total severity) was significantly greater ($t = 2.03$, $p < 0.03$) immediately after exposure as compared to before. The nausea ($t = 1.76$, $p < 0.05$), oculomotor disturbances ($t = 2.01$, $p < 0.03$), and disorientation ($t = 1.81$, $p < 0.05$) subscale scores at post-exposure were all significantly greater than at pre-exposure. There were no significant differences detected between pre-exposure SSQ scores and 30 minute post-exposure SSQ scores (nausea – $t = 0.87$, $p < 0.2$; oculomotor – $t = 1.38$, $p < 0.09$; disorientation – $t = 1.15$, $p < 0.13$; total severity – $t = 1.24$, $p < 0.11$); nor with immediate post-exposure and 30 minute post-exposure SSQ scores (nausea – $t = 1.18$, $p < 0.12$; oculomotor – $t = 0.97$, $p < 0.17$; disorientation – $t = 0.92$, $p < 0.19$; total severity – $t = 1.11$, $p < 0.14$). However, self-reports of sickness for the two post- exposures were highly correlated ($r = 0.87$, $p < 0.001$).

3.2. Gender effects on VE sickness

The mean SSQ scores for females after VE exposure was 35.5 ($SD = 43.4$), whereas the mean sickness for males was 10.43 ($SD = 16.9$). The greater vulnerability to sickness for the 14 female participants as compared to the 20 male participants was significant ($t = 5.03$, $p < 0.0001$). This corresponds to similar findings in a variety of flight and driving simulator studies (Kennedy *et al*, 1995).

3.3. Motion history questionnaire

The mean Motion History Questionnaire (MHQ) score was 4 ($SD = 1.34$), but was not predictive of post-exposure ($r = 0.11$, $p > 0.05$).

3.4. PT measures as an assessment of aftereffects from exposure to a virtual environment

The average difference between the participants' pre- and post- exposure pointing errors was used as the measure of adaptation which was elicited during exposure to the virtual environment. Because there were no pre- or post- errors detected for any eyes-open comparison, there were no pre/post differences and these data are

Table 1
Simulator sickness questionnaire scores (SSQ)

	Nausea	Oculomotor	Disorientation	Total severity
Pre-exposure	6.58 (15.74)	6.53 (9.44)	7.68 (14.69)	7.87 (13.24)
Post-exposure	15.46 (27.03)[a]	14.64 (19.63)[a]	21.60 (43.0)[a]	19.09 (30.64)[a]
30 minutes post	9.54 (14.87)	10.72 (16.27)	13.92 (29.76)	12.77 (20.81)

Standard deviations appear in parentheses.
[a]$p < 0.05$ for pre-versus post- exposure.

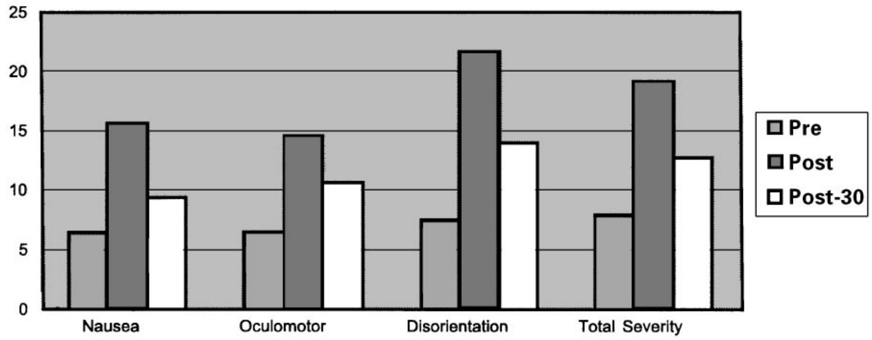

Fig. 2. Simulator sickness questionnaire scores.

not reported. There were three determinations at each condition (i.e. left/center/right; 0/5 second delay) and the average pre-score for each determination for each subject was subtracted from the appropriate post-score determination and then averaged. These differences appear separately for both horizontal (X-direction) and vertical (Y-direction) errors in Tables 2 and 3, respectively. It may be seen that all comparisons for X show a positive (i.e. leftward) shift from pre- to post- but the differences, while consistent, were small (average = 2.12 mm) and not statistically significant ($t = 1.81$, $p < 0.08$). There was however a significant ($t = 2.17$, $p < 0.038$) upward shift from baseline (average = 2.89 mm) following exposure to the virtual environment.

Changes were stronger in the vertical dimension than horizontal and there was a suggestion that what effects were found were stronger in the center position and with the longer delays, but these differences were not consistent. Individual differences in past pointing change averaged over all conditions were not correlated with the severity of cybersickness ($r = 0.05$) even when corrected for attenuation due to unreliability of the measures ($r = 0.11$).

Table 2
Mean horizontal error in pointing performance, with zero and 5-second delays at the center, left, and right orientations

	Orientation			
Delay (s)	Center	Left	Right	Average
0	− 2.13	− 2.41	− 3.85	− 2.80[a]
5	− 1.87	− 2.48	− 0.48	− 1.61
Average	− 2.00	− 2.44	− 2.17	− 2.20

[a] $p < 0.05$ for post- minus pre- exposure difference.
Note: The dependent measure is the post- minus pre-exposure difference, in millimeters.

Table 3
Mean vertical error in pointing performance, with zero and 5-second delays at the center, left, and right orientations

	Orientation			
Delay (s)	Center	Left	Right	Average
0	5.41[a]	− 0.28	1.26	2.13
5	6.52[a]	2.68	2.02	3.74[a]
Average	5.96[a]	1.20	1.64	2.93[a]

[a] $p < 0.05$ for post- minus pre- exposure difference.
Note: The dependent measure is the post- minus pre- exposure difference, in millimeters.

4. Discussion

4.1. Prediction of sickness

Past studies using the MHQ (Kennedy *et al*, 1992) and SSQ in larger samples show strong and positive correlations. In this study, however, the MHQ scores were not significantly correlated with post- exposure SSQ total sickness scores. Although the correlations were in the predicted direction, they were extremely low ($r = 0.11$). However, we did find support for the gender differences in susceptibility which have been reported by others. The failure to obtain a relationship between history and susceptibility is disappointing because it is clear that if individuals experiencing aftereffects cannot be identified, then this problem cannot effectively be managed. Thus, new means of predicting VE aftereffects from histories may be needed to measure and manage the aftereffects from VE exposure.

4.2. Post effects – sickness

We showed that, after 30 min exposure to a VE, participants reported more sickness measured by the SSQ than before exposure, significant ($p < 0.03$) immediately after exposure. The level of the symptoms experienced by participants 30 min post-VE exposure did not completely return to pre-exposure levels, although this delay in recovery was not significant (total severity $p < 0.11$). This implied lack of sensitivity emphasizes the need for more objective measures of the aftereffects from VE exposure so that full physiological recovery can be systematically identified. If available, a complete battery of such techniques could detect recalibrations in proprioceptive, vestibular, and oculomotor functioning that could compromise the well-being of users.

4.3. Aftereffects — pointing test

This study had as its focus the evaluation of proprioceptive changes related to VE exposure. Eyes-open pointing test scores showed no change from baseline, but eyes-closed revealed changes when post-exposure scores were compared with pre-tests. Stronger effects were found for the vertical (Y) dimension where the average vertical shift was 2.93 mm upward. The vertical movement in a center orientation provided the most sensitive measure, with a mean shift of 5.96 mm upward. While the differences are small and only statistically significant for the vertical (Y) plane, we had an opportunity to compare the findings from this study with another experiment which used a different VE device but the same past pointing test (Kennedy *et al*, 1996b). In that study, using a Virtual i-O i-glasses! headset and the game Ascent, participants were exposed to the VE for 40 min with other differences (e.g. monocular and stereo presentations were compared, posture was tested).

In order to facilitate comparison, we have reproduced the data that are comparable for the two experiments. It may be seen that in both experiments, post-sickness (Table 4) was higher than the pre-test scores and all of these pre/post differences were statistically significant. The average post- minus pre- past-pointing changes with eyes closed (Tables 5 and 6) were all significant ($p < 0.006$) in Experiment 2 and in the same direction as was found in Experiment 1. These findings may be seen in Tables 5 and 6 and we have combined X and Y changes and show them graphically for both experiments in Fig. 3.

When the average sickness score for each subject was correlated with the average aggregate post-effect for past pointing again, as in Experiment 1, the correlation was essentially zero ($r = 0.07$) even when corrected for reliability attenuation (i.e. $r = 0.15$). The possibility that post-effects such as sickness and past pointing may not be

Table 4
Simulator sickness questionnaire (SSQ) post- minus pre- exposure sickness differences for Experiments I and II

	Nausea	Oculomotor	Disorientation	Total severity
Experiment I	8.88[a]	8.11[a]	13.92[a]	11.22[a]
Experiment II	13.41[b]	12.70[b]	16.93[b]	16.07[b]

[a] $p < 0.05$ for post- minus pre- exposure difference.
[b] $p < 0.01$ for post- minus pre- exposure difference.

Table 5
Mean horizontal error in pointing performance, with zero and 5-second delays at the center, left, and right orientations

	Orientation			
Delay (s)	Center	Left	Right	Average
0	− 6.51[a]	− 1.41	− 2.90	− 3.61[a]
5	− 10.72[a]	− 3.09	− 6.31[a]	− 6.70[a]
Average	− 8.61[a]	− 2.25	− 4.60[a]	− 5.16[a]

[a] $p < 0.05$ for post- minus pre- exposure difference.
Note: The dependent measure is the post- minus pre-exposure difference, in millimeters.

Table 6
Mean vertical error in pointing performance, with zero and 5-second delays at the center, left, and right orientations

	Orientation			
Delay (s)	Center	Left	Right	Average
0	9.99[a]	1.15	2.30	4.48[a]
5	10.69[a]	3.98	1.21	5.29[a]
Average	10.34[a]	2.56	1.75	4.89[a]

[a] $p < 0.05$ for post- minus pre- exposure difference.
Note: The dependent measure is the post- minus pre-exposure difference, in millimeters.

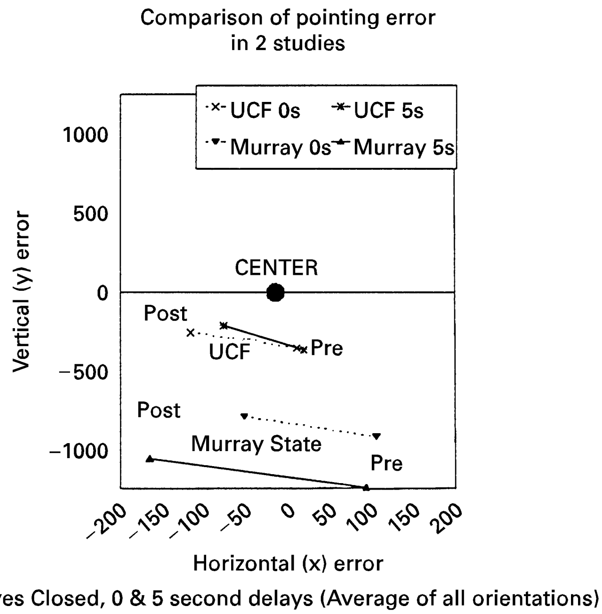

Fig. 3. Post- minus pre- pointing changes in two experiments.

correlated suggests both should be monitored in VE aftereffect studies.

In summary, using the PT, the results from the Kennedy *et al* (1996b) study demonstrated highly significant ($p < 0.001$) shifts in both the upward (4.9 mm) and leftward (5.2 mm) directions. The average shift (5.03 mm) was approximately twice as large as the average shift found in the present study (2.57 mm). This reasonable replication of results is highly encouraging because it implies that the PT may provide evidence of generalized changes across VE systems. It is interesting to note the relationship between the stimulus strength, as measured by the SSQ, and the magnitude of the average shift, as measured by the PT, found in the two studies. Both the sickness symptomatology and the average shift were more than 50% stronger for the Ascent VE as compared to the VE used in the present study. This implies a hypothesis that the magnitude of the proprioceptive recalibration may be proportional to some aspect of the VE stimulus. Whether this is due merely to the duration of exposures or some other factors remains to be determined.

However, the magnitude of the directional errors found in these studies is consistent with several past related studies (Darling and Miller, 1993; Helms-Tillery *et al*, 1991; Soechting and Flanders, 1989) that demonstrated small directional pointing errors. These studies all demonstrated that errors in reach *distance* are consistently of much greater magnitude than errors in direction. The simplicity and portability of the current PT approach justified evaluating directional errors first to determine if they were sensitive to adaptive changes related to VE exposure. Due to the significant findings, further evaluations should examine the relative effectiveness of using directional versus distance errors to detect adaptive changes in motor performance due to VE exposure. While the measurement of distance errors requires more sophisticated apparatus, if they are more sensitive than directional errors to adaptive changes related to VE exposure their use may be justified.

It should be pointed out that during the eyes-closed condition, participants were not provided with visual or tactile information about the accuracy of their pointing performance. The participants thus had to adjust their motor performance by comparing kinematic plans and proprioceptive feedback from the actual trajectory used. DiZio and Lackner (1995) and Lackner and DiZio (1994) demonstrated that movement trajectory is monitored accurately and individuals use proprioceptive information (i.e. deviation from intended path) to adjust movement control. If the proprioceptive information being used to make the adjustments was inaccurate (due to adaptation related to VE exposure), this should then result in displaced movement control, as was seen in the eyes-closed condition. It would appear that during the eyes-open trials, when visual information was available, the sensorimotor integration process (Wolpert *et al*, 1995) weighed this input in determining its final destination, thereby resulting in accurate movement control.

We are aware that the results regarding pointing accuracy are small effects and the directionally specific results (i.e. a shift up and to the left), even from two independently conducted experiments at two different laboratories, could be explained by any one of several time course effects on behavior (learning, boredom, habituation, etc.). However, the changes we obtained are rational, are consistent with other motor aftereffects such as postural change (Kennedy *et al*, 1993c) and increased levels of motion sickness (Kennedy *et al*, 1989), and related effects have been reported by others (Biocca and Rolland, 1998; Sanes *et al*, 1995). These latter studies imply that overlapping movement representations in the human cerebral cortex, M1, can form adaptive networks to mediate complex motor phenomena, thus indicating *activity-dependent* synaptic plasticity. If after activity in a VE, proprioceptive feedback were inappropriate for real-world task requirements (having been recalibrated due to activities performed in the VE), and visual/tactile accuracy information were unavailable, an adaptive recalibration in movement control would be expected. This is consistent with the results of the current study. These results suggest that during VE exposure, an individual will detect a discrepancy between their movements and the corresponding visual feedback from the VE. This will trigger the need for compensatory adaptive replanning of movement control, which upon post- exposure will result in decreased accuracy in the perception of limb position and movement. Thus, when participants began their post-exposure PT activities with their hand in their lap and their view of the hand blocked by the visor, the perception of their felt limb position would have been inaccurate due to proprioceptive recalibrations engendered by the virtual environment. In the eyes-open condition participants could transform this inaccurate proprioceptive information into a visual coordinate system (Darling and Miller, 1993) and adjust their movements accordingly. In the eyes-closed condition, however, the initial proprioceptive feedback and the added kinesthetic feedback during the limb movement would be 'accurate' according to the recalibrated system and thus displacements would persist, as was found in this study.

5. Conclusions

The results from this study demonstrated that when participants pointed to remembered target locations, and were denied visual and tactile feedback about pointing accuracy, they made consistently greater errors in their pointing performance after exposure to a VE as compared to before exposure. The systematic pointing errors after VE exposure cannot be attributed to changes in the visual system per se since they occurred in an eyes-closed condition and we believe are not likely due to fatigue because they were absent when the pointing task was performed in the eyes-open condition. These systematic errors, while small, were also consistent, being found in two diverse virtual environments and they occurred in connection with reports of cybersickness post-exposure. This suggests that proprioceptive information about felt limb position, which is continuously monitored and used to plan subsequent movements, may be altered during VE exposure and could lead to adaptive changes in proprioception, which results in movement errors. To the extent that this shift is representative of VE aftereffects, it implies that users may be in a physiological state which could compromise their health and safety upon departure from a VE experience.

For some time we have been using self-reports of symptoms to index suitability of simulators and VE systems. Generally, those with higher incidences would obtain poorer evaluations. We would have assumed, indeed predicted, that those who had symptoms would also have other aftereffects such as postural disequilibrium and pointing test changes. The fact that changes in both kinds of effects (symptoms and past pointing changes) occurred in this study, but were uncorrelated, implies at the very least that both should be measured in VE aftereffect studies if each has potential consequences.

These results suggest that pointing errors could serve as an integral part of a virtual environment adaptation assessment test battery by detecting proprioceptive recalibrations. Such a battery could be used to ensure that aftereffects from VE exposure have dissipated and thus that users should be safe to return to their normal daily activities. As the scientists from the space program have long known (cf., Reschke *et al*., 1994a; Reschke *et al*., 1994b), other tests (vestibulo-ocular reflex, oculomotor function, Hoffman reflex) may also be useful measures.

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