Aftereffects and Sense of Presence in Virtual Environments: Formulation of a Research and Development Agenda

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Aftereffects and Sense of Presence in Virtual Environments: Formulation of a Research and Development Agenda

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This report represents a committee summary of the current state of knowledge regarding aftereffects and sense of presence in virtual environments (VEs). The work presented in this article, and the proposed research agenda, are the result of a special session that was set up in the framework of the Seventh International Conference on Human Computer Interaction. Recommendations were made by the committee regarding research needs in aftereffects and sense of presence, and, where possible, priorities were suggested. The research needs were structured in terms of the short, medium, and long term and, if followed, should lead toward the effective use of VE technology. The 2 most critical research issues identified were (a) standardization and use of measurement approaches for aftereffects and (b) identification and prioritization of sensorimotor discordances that drive aftereffects. Identification of aftereffects countermeasures (i.e., techniques to assist users in readily transitioning between the real and virtual worlds), reduction of system response latencies, and improvements in tracking technology were also thought to be of critical importance.

1. INTRODUCTION

Virtual environment (VE) technology is an advancing computer interface medium that allows its users to become immersed in and interact with computer-generated worlds. In some VEs, users don helmet-mounted displays that track their head movements and appropriately update the visual imagery as the users look and "move" (generally via a mouse or dataglove) about the virtual world. In others, the visual display is projected on a large screen, and in still others there is no visual display but a haptic or an auditory one instead. Alternatively, many display systems could be used together. The modeled world presented by the computer can take on many forms, such as the topography of a single molecule, the interior architecture of a building, or interstellar space. The goal of a VE can be scientific visualization, training a sensorimotor or cognitive task, or entertainment. What sets this technology apart from its ancestors is that in VE systems users receive multisensory stimuli (i.e., visual, auditory, and sometimes haptic) that are intended to provide a sensation of actual interaction with the virtual world. Although this description sounds intriguing, the expectations of individuals who interact with VEs well exceed the current capabilities of the technology. For example, patrons of a new VE theme park

This document in its entirety is based on the information derived from a special session (i.e., roundtable discussion) at HCI International '97, the Seventh International Conference on Human Computer Interaction to which participants were invited. The session was organized by Kay Stanney and Gavriel Salvendy. A draft copy of this article was sent to all members of the roundtable for their input regarding any revisions, changes, additions, and editing. The article presented here represents the integration of input received from all participants of the roundtable and forms the final product of this special session. The roundtable contributors (i.e., managers, engineers, industrial consultants, and researchers) are listed in alphabetical order.

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at the World Trade Center expressed feelings of being dazzled, yet disappointed; others found the experience to be much less overwhelming than they expected (Sherman, 1993). Beyond the excessive media "hype" that has exaggerated VE capabilities, some of this disappointment may by due to the fact that today's VEs often engender motion sickness and lack a *sense of presence* or immersion in the computer-generated environment. The incidence and severity of these problems are as variable as the hardware and software used to implement VE systems.

Thus, although VE technology is advancing rapidly and applications driven by this technology are expected to be commonplace within the next decade (Boman, Piantanida, & Schlager, 1993), the use of current VE systems is limited by maladies (i.e., motion sickness and physiological aftereffects) that may compromise the well-being of users once interaction with the VE has ceased. In addition, techniques that specify how to design VEs most effectively to optimize training and human performance (e.g., how much realism is required) have not been devised. The necessity for managing the effective use of this technology is progressively acknowledged by an increasing proportion of the research community, as well as industry, and scientific and technical committees (e.g., Chien & Jenkins, 1994; Durlach & Mavor, 1995). In the United Kingdom for instance, in 1993 the Engineering and Physical Sciences Research Council (EPSRC) funded an early study of the potential for industrial applications of VE (Wilson, D'Cruz, Cobb, & Eastgate, 1996). One of the perceived barriers to industrial use—concern over harm to VE participants or to their subsequent performance—became the focus of a subsequent experimental and field study funded by the Health and Safety Executive (i.e., Virtual Reality Induced Symptoms and Effects; see Cobb, Nichols, Ramsey, & Wilson, 1998; Nichols, Cobb, & Wilson, 1997; Wilson, 1996). These efforts identified that among the ingredients of success required to realize the full potential of the emerging VE technology, the identification of techniques to minimize or eliminate aftereffects and achieve sense of presence are considered to be of critical importance.

2. DESCRIPTION OF THE SPECIAL SESSION

2.1. Objective

To address research issues related to aftereffects and sense of presence in VE technology, a special session was held at the Seventh International Conference on Human Computer Interaction. The objectives of this session were to (a) summarize the state of knowledge regarding aftereffects and sense of presence in VEs and (b) devise a short-, medium-, and long-term research and development (R&D) agenda to promote the effective use of VE technology. The specific problem statement addressed by the group was:

> To define the critical short-, medium-, and long-term research, design, and development issues relevant to enhancing individual and organizational performance in VEs and in reducing or preventing deleterious side effects and aftereffects of exposure to these environments.

A concerted and timely effort is needed to identify research priorities related to aftereffects and sense of presence. Resulting recommendations can be used to advise current and future initiatives across the world (such as the U.K. Virtual Reality Induced Symptoms and Effects Programme). In this section, a brief review of the session participants and the approach used to address the problem statement are provided.

2.2. Participants

Twenty-five experts (the authors of this article) participated in this effort. This group consisted of 20 men and 5 women from 14 different organizations. Each participant had several areas of expertise: 17 were involved in human factors, 7 in usability evaluation, 7 in VE software, 3 in VE hardware, 10 in VE applications, 1 in networked and collaborative VE, 1 in legislation, 3 in industrial policy, and 2 in standardization. The 14 participating organizations comprised 3 federal agencies (NASA, Army, Navy), 2 contracting companies (Essex Corporation, Logicon Technical Services), and 9 research and academic institutions (Brandeis University, Fraunhofer-Institute for Industrial Engineering, Massachusetts Institute of Technology, Purdue University, University of Central Florida, University of Cincinnati, University of Nottingham, University of Reading, Wright State University). There was also one high-technology private consultant.

2.3. Materials

Sixteen of the participants contributed papers, and 11 participants presented these papers at the Seventh International Conference on Human Computer Interaction. These papers summarized the participants' research and position related to aftereffects or sense of presence in VEs. This information was used as the foundation for the consolidation of the literature presented in Section 3. Eighteen of the participants were in attendance at the special session. During the special session a questionnaire was used to gather background information concerning the participants and facilitate targeted response and data collection on a number of issues pertaining to VE technology. The questionnaire included four targeted questions involving the state of scientific knowledge, technological impediments, the role of national institutions, and industrial impediments to the effective use of VE technology. The questionnaire was circulated during the session, along with a document that provided background information on the meeting's objectives, rationale, themes, structure, and organization. The questionnaire results are summarized in Section 4.

2.4. Meeting Organization

The meeting was organized as a roundtable discussion, including a chair (first author) and a secretary. Minutes were kept by the secretary and were circulated to all participants 1 month after the meeting. The driving themes of the special session centered around three major topics, which covered (a) measuring, managing, and predicting human performance implications of aftereffects; (b) achieving, measuring, and predicting human performance implications of sense of presence; and (c) specification of the relation between sense of presence and aftereffects and its implication for human performance. Each theme covered a broad range of issues suitable for discussion during the meeting. Participants were expected to contribute actively toward the identification of the relevant issues in each of the themes, the assessment of the available related scientific and technological knowledge, and the definition of an R&D agenda for the short, medium, and long term that should lead to the effective use of VE technology.

3. CONSOLIDATION OF THE LITERATURE

In this section a consolidation of the progress in the scientific areas of aftereffects and sense of presence in VEs is provided. The incredible variety of VE systems and applications required some subjectivity in the consolidation process. Consensual judgment was often required to extract general conclusions from sets of studies that used different hardware and software or had different content and purposes. We note these difficulties in several places in the text of this article. This review provides insight into many of the research issues identified in Sections 4 and 5 as being critical to the effective use of VE technology.

3.1. Aftereffects

Motion sickness-like symptoms and other aftereffects (i.e., balance disturbances, visual stress, altered hand–eye coordination) are an unwanted by-product of VE exposure. The sickness related to VE systems is commonly referred to as *cybersickness* (McCauley & Sharkey, 1992). There is concern that continued development of VE technology may be compromised by the presence of these maladies, which are experienced by a significant proportion of users (Chien & Jenkins, 1994). A number of the VE-related ill effects are similar to the motion sickness symptoms reported in the 1980s by military air crews and NASA test pilots following exposures to flight simulators (Frank, Kennedy, Kellogg, & McCauley, 1983; Kennedy, Jones, Lilienthal, & Harm, 1993; Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989; McCauley & Cook, 1986).

Important problems related to cybersickness and aftereffects in VEs that require research are: (a) How can prolonged exposure to VE systems be obtained? (b) How can aftereffects be characterized? (c) How should they be measured and managed? (d) What is their relation to task performance?

Specifying Means to Achieve Prolonged VE Exposure

Strategies need to be identified to obtain prolonged exposure to VE systems when required (e.g., for training purposes). Means of identifying who is susceptible and how strong VE stimuli are can both assist in this matter.

Individual Susceptibility. Age, gender, motion sickness histories, prior experience, and individual factors have been shown to be useful in identifying persons who are susceptible to provocative motion environments. Before the age of 2, children appear to be immune to motion sickness, after which time susceptibility increases until about the age of 12, at which point it declines again. Those over 25 are about half as susceptible as they were at 18 years of age (Mirabile, 1990). Whether or not this trend will hold in VE systems is not currently known.

Some studies found that women generally experience greater motion sickness than men (Kennedy, Lanham, Drexler, & Lilienthal, 1995). In one VE study a similar gender contrast was reported (Kennedy, Stanney, Dunlap, & Jones, 1996). In this study the mean symptomatology for women after VE exposure was 3.4 times greater than for men. This gender difference is thought to be hormonally related (Schwab, 1954). It is possible that at certain phases of the menstrual cycle a woman is more susceptible to motion sickness than at others. In studies of postoperative nausea and vomiting the severity of sickness has been found to be dependent on the stage in the menstrual cycle and if a woman is on the contraceptive pill (Beattie, Lindblad, Buckley, & Forrest, 1991; Honkavaara, Lehtinen, Hovorka, & Korttila, 1991; Ramsay, McDonald, & Faragher, 1994). To address these issues in VE systems, Ramsey (1997) and Ramsey and Wilson (1998), in a program of work at the University of Nottingham, is evaluating the influence of menstrual phase on susceptibility to aftereffects in a VE system by comparing self-report of symptoms with changes in heart rate and salivary cortisol levels.

The Motion History Questionnaire (MHQ), which was developed 30 years ago to study air sickness and disorientation due to Coriolis stimulation, is often used to assess susceptibility to motion sickness (Kennedy & Graybiel, 1965). The MHQ assesses susceptibility based on past occurrences of sickness in inertial environments. Using this 15-item paper-and-pencil questionnaire, individuals list past experiences in provocative motion environments. Scores on the MHQ are generally predictive of an individual's susceptibility to motion sickness in physically moving environments. In a recent VE study (Kennedy, Stanney, et al., 1996), however, MHQ scores were not significantly correlated with preexposure, immediate postexposure, or 30-min postexposure Simulator Sickness Questionnaire (SSQ) scores. Thus, either the MHQ needs to be modified to accurately predict susceptibility in VE environments or alternative approaches are required.

Previous exposure to a provocative environment influences susceptibility to motion sickness. Over repeated, intermittent, short exposures to the same environment, habituation tends to occur in which symptomatology decreases (McCauley & Sharkey, 1992). Biocca (1992) cited evidence that the occurrence and severity of sickness noticeably decreases after four to six exposures in simulators, whereas Regan (1995) found a dramatic decrease in sickness incidence over the course of four repeated exposures. Kennedy, Jones, Stanney, Ritter, and Drexler (1996) found marked reductions in sickness in the second of two 40-min VE exposures. Kennedy, Lane, Berbaum, and Lilienthal (1993) found that for repeated exposures in simulators to be effective in desensitizing individuals to sickness, the intersession interval should be short (1 week or less). This finding is consistent with other reports of motion sickness in which: (a) some adaptation was retained during 7-day intervals between slow rotation room exposures, but not during a 30-day interval (Kennedy, Tolhurst, & Graybiel, 1965); and (b) intersession intervals in Navy flight trainers of 1 day or less showed no evidence of increased tolerance, nor did those greater than 6 days apart, whereas those 2 to 5 days apart appeared to be optimum (Kennedy, Lane, et al., 1993).

Post-VE exposure effects are also dependent on individual factors. For example, binocular vision develops early and is relatively stable by the early school years, but the age at which children should be allowed unconstrained access to head-mounted display (HMD) systems is still open to debate. Similarly, adults vary in the robustness of their visual systems. It can be predicted that someone with unstable binocular vision may experience stronger postexposure effects if there are stimuli that place some stress on either the *accommodation* (focal) system, *vergence* system, or the *cross-links* between them (Wann, Rushton, & Mon-Williams, 1995). To date, however, the research into visual aftereffects has been almost exclusively on users with robust binocular vision, and for ethical reasons it is difficult to investigate the consequences of long-term or repetitive exposure on high-risk individuals or children. Individual variations in interpupillary distance (IPD) may also have consequences for calibration of HMDs. Physical measurement and adjustments to suit individual IPDs are often impractical (Rushton, Mon-Williams, & Wann, 1994), but such adjustments can be tuned to the user with appropriate software routines (Wann, Rushton, & Mon-Williams, 1995). There is evidence to suggest, however, that small errors in IPD setting will produce negligible aftereffects on the visual system (Howarth, in press).

Stimulus Strength. Means of assessing the strength of a VE stimulus (i.e., how likely it is to cause cybersickness and aftereffects) are also required. Such measurement techniques could assist with both the specification of usage protocols and setting of redesign priorities. General system factors thought to influence stimulus strength include: system consistency (Uliano, Kennedy, & Lambert, 1986); lag (So & Griffin, 1995); mismatched IPDs (Mon-Williams, Rushton, & Wann, 1995; Mon-Williams, Wann, & Rushton, 1993, 1995a); large field-of-view (FOV; Kennedy & Fowlkes, 1992); update rate (So & Griffin, 1995); spatial frequency content (Dichgans & Brandt, 1978, cf. Fig. 6, p. 770); visual simulation of action motion (i.e., vection; Kennedy, Berbaum, Dunlap, & Hettinger, 1996), and unimodal and intersensorial distortions (both temporal and spatial).

Exposure duration and number of repeat exposures have also been shown to affect the level of motion sickness experienced by users. In a recent meta-analysis of exposure duration data in simulator systems, Kennedy, Stanney, and Dunlap (in press) verified that exposure duration is positively related and repetition negatively related to total sickness. This analysis indicated that additional research is needed to determine the optimal length of a single exposure and the optimal intersession interval to facilitate habituation in VE systems. To optimize the use of VE systems, a set of duration studies is required that use different display systems and require different activities of the user.

Within specific domains it is valuable to identify the primary parameters that may induce aftereffects and effect their "strength." For example, in the domain of motion sickness, DiZio and Lackner (1997) identified large end-to-end visual update delays and a large FOV as significant etiologic factors in a VE that used an HMD. They emphasized that experimenters must devise their own ways of measuring these values (see Rinalducci, Mapes, Cinq-Mars, & Higgins, 1997). The manner in which individual software and hardware components can be integrated varies greatly; thus, the manufacturer's specifications concerning the individual component parameters (if they exist) will not suffice. Accurate measurements are the only way to achieve goals such as establishing guidelines for VE designers to follow (e.g., establishing the visual update delay below which motion sickness is not a problem). Readers of the VE literature should be cautious about making such recommendations or drawing any other conclusions from reports that do not adequately specify the performance of the systems investigated. Measuring the relevant aspects of system performance is one side of the measurement problem this report emphasizes, measuring user responses is the other side.

In the domain of the visual system the mismatch between accommodation and vergence demands has been highlighted (Howarth & Costello, 1996; Mon-Williams et al., 1993; Wann, Rushton, & Mon-Williams, 1995). Although IPD settings may not be critical (Howarth, in press) it can be demonstrated that a mismatch between the orientation of the optical axes of a display and the axes assumed for software generation may produce large errors (Wann, Rushton, & Mon-Williams, 1995). Although FOV and display resolution may affect the usability of a display system and lead to motion sickness, they have not been shown (with the ballpark of current displays) to be critical factors in producing visual stress. Finally, it is pertinent to note that both common and unique stimulus factors can arise from either HMD or spatially immersive displays (SIDs or Cave Automatic Virtual Environments; see Cruz-Neira, Sandin, & DeFanti, 1993). A unique factor that is present in an HMD is lag between head movement and update of the visual display. In common with an HMD, a stereoscopic SID may also present a discord between accommodation and vergence stimuli (Wann & Mon-Williams, 1997). In addition to this, a SID may, from some viewing positions, require a small degree of aniso-accommodation (unequal focus across the two eyes). It can be demonstrated that, under intensive viewing conditions, even a desktop stereoscopic display can produce aftereffects for the binocular visual system, whereas a nonstereoscopic display will not (Mon-Williams & Wann, in press).

Characterizing Aftereffects

In reviews of VE technology, the summary works of Chien and Jenkins (1994), Durlach and Mavor (1995), and Kalawsky (1993) all noted the importance of the cybersickness problem, as well as the possibility of aftereffects. Although the term cybersickness evokes thoughts of overt nausea during VE use, it actually comprises a number of less obvious effects. Perhaps the most dangerous effect that would not be uppermost in the mind of a VE user is disturbed locomotor and postural control following exposure to a VE system. Perceptual–motor disturbances have been observed with the use of VE devices (Kennedy, Stanney, Ordy, & Dunlap, 1997; Rolland, Biocca, Barlow, & Kancherla, 1995). The occurrence of these aftereffects has been noted with increasing frequency in the scientific and technical literature on VE technology (e.g., Barfield & Weghorst, 1993; Biocca, 1992; Carr & England, 1995; Chien & Jenkins, 1994; Durlach & Mavor, 1995; Kalawsky, 1993; Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992; Pausch, Crea, & Conway, 1992). It has become widely accepted among scientists and technologists involved in the development of this technology that these aftereffects represent a significant concern that needs to be addressed.

Other insidious effects of VE exposure may exist as well. Drowsiness and fatigue are among the most common symptoms of simulator exposure (Kennedy, Massey, & Lilienthal, 1995) and can be listed among the more severe symptoms as well (see Ungs, 1988). Several researchers have warned of the possibility for *sopite syndrome* (Dizio & Lackner, 1992; Graybiel & Knepton, 1976), characterized by lowered arousal or mood during or after VE use (Kennedy, 1994; Lawson, Rupert, Guedry, Grissett, & Mead, 1997; Leibowitz, Ebenholtz, Held, Kennedy, & Lackner, 1990). If the sopite syndrome occurs among VE users, it would be likely to affect performance without being fully detected by the afflicted person (Kennedy, 1994; Lawson & Mead, in press).

Strictly speaking, any effect of a VE that is observed after the participant has returned to the physical world qualifies as an aftereffect (Welch, 1997). Thus, the term applies not only to the well-known delayed "flashbacks" from aircraft simulator training (e.g., Baltzley, Kennedy, Berbaum, Lilienthal, & Gower, 1989), but to any fatigue, malaise, motion sickness, headache, eye strain, drowsiness, and the like experienced while in the VE and persisting for some time afterward. Many of the aftereffects identified result from the user's adaptation to the VE in question.

Negative aftereffects are a ubiquitous observation in studies of adaptation to optical rearrangements of vision (e.g., Dolezal, 1982; Welch, 1978). For example, after participants who have been wearing light-displacing wedge prisms overcome their initial target-pointing errors and then remove the prism goggles, their early attempts to point with normal vision err in the direction opposite the errors made when they first wore the prisms. It is because these aftereffects are in the opposite direction that they are termed negative. Similarly, if after leaving a VE, users experience perceptual or perceptual–motor disruptions opposite those that occurred when first entering the VE, it can be concluded that they have adapted to some extent. A variety of negative aftereffects to VEs have been reported (e.g., Kennedy & Stanney, 1996; Rolland et al., 1995).

Why does VE adaptation occur in the first place? The answer is that it is the natural and automatic response to an intersensorily imperfect VE and is elicited due to the plasticity of the human nervous system (Dolezal, 1982; Graybiel et al., 1965; Welch, 1978). Due to technological flaws (e.g., inadequate computer power, slow update rate, sluggish trackers, incorrect programming), the user may be confronted with one or more intersensory discordances (e.g., a disparity between seen and felt limb position). *Proprioception* (felt position) is known to be prone to drift (Wann & Ibrahim, 1992) and easily biased (Lackner, 1988; Plooy, Tresilian, Mon-Williams, & Wann, in press; Rock & Victor, 1964). There is also evidence that visual displacement may give rise to a proprioceptive illusion, such that the user may "feel" their hand is in the seen location (Hay, Pick, & Ikeda, 1963; Mon-Williams, Wann, Jenkinson,

& Rushton, 1997). Hence, the discord may not be apparent to the user until critical performance errors arise in actively interacting with the VE, thereby stimulating adaptive learning. Held (1965) argued that the ability to adapt to such discordances is present from birth, as babies and children acquire and maintain motor control of their environmental interactions.

Kennedy, Hettinger, and Lilienthal (1990) defined adaptation as the vehicle by which stimuli lose their "novelty." Reason (1970) believed that adaptation is the most promising answer to sickness-inducing conditions because over 95% "of all susceptible individuals show adaptation to the conditions that produce motion sickness in everyday situations" (p. 391).

Young and Oman (1969) characterized the vestibular adaptation process "as a shift of reference level based on the recent history of cupula [a vestibular organ] displacement" (p. 1076). Reason and Brand (1975) referred to it as "perceptual adaptation," in which conflicting signals from two or more perceptual systems become "normalized" to the point that there are no more symptoms of sickness. In other words, the intersensory signals are no longer perceived by the brain as being in conflict. Such adaptation is characterized by a decline in the initial response to an altered stimulus (i.e., reduced cybersickness), development of an altered response following prolonged exposure to the change (i.e., adaptation), and a continuation of the adapted response (i.e., an aftereffect) once the stimulus is removed (Parker & Parker, 1990). Although such adaptation may sound advantageous, aftereffects may make individuals maladapted for the return to the "real" world once VE interaction concludes. It has been found that better adaptation to optical rearrangements is associated with more substantial or lasting negative aftereffects (e.g., Welch, 1978). This relation may hold for VE adaptation as well.

Several researchers recently provided empirical evidence that when VE devices present altered visual conditions, adaptation does occur. Rolland et al. (1995) warned of and demonstrated such a problem with see-through HMDs. In their study, they found that exposure to a VE resulted in pointing errors in the y and z dimensions and a 43% reduction in manual task speed. They observed that participants' performance slowed down immediately when commencing interaction with a VE; the participants' initial reaching movements were "uncoordinated," "uncertain and inaccurate." Rolland et al. stated that this early exposure performance issue drives adaptive changes in the participants' perceptual system during exposure to a VE, leaving the participants "miscalibrated for the real world" once the exposure is complete. Although they did not specifically measure these latter assumed aftereffects, they did anecdotally note their presence.

There are sensory conflicts, however, in which it is difficult for the user to arrive at a compensation (Wann & Mon-Williams, 1997). In the case outlined earlier of "yoked" displacing prisms, there is a linear (angular) displacement of visual location of objects. In this case, the user must learn a new mapping between visual locations and proprioceptive positions. If a user is exposed to "base-in" or "base-out" prisms, then these alter the binocular vergence angle required to look at objects in depth, but, once again, an adaptive compensation would be to learn a new mapping between a range of vergence angles and a range of accommodation states. This is not an analogue of many VE systems. Many current stereoscopic displays present the user with a range of binocular targets to which they may verge, with a single focal depth for the image plane. A mapping of a range of vergence positions to a single accommodative state has no simple compensation (see Figure 1 or reference Wann & Mon-Williams, 1997). The only potential adaptation to this setting would be to null the natural cross-links between accommodation and vergence (AC/A and CA/C[1]). There is debate over the plasticity of the AC/A and CA/C systems (Judge & Miles, 1985; Miles & Judge, 1981; Schor, 1991), but stereoscopic VEs provide a very unusual discord. There is some evidence that the cross-link influence can be nulled, but that it may be particularly stressful for the individual (Mon-Williams, Wann, & Rushton, 1995c; Mon-Williams, Gray, & Wann, 1997). If the VE user is directing vision predominantly to a small depth range (e.g., either close working or distance viewing), then local adaptations are feasible. It is therefore debatable whether transient postexposure changes in binocular function reflect stress or an adaptive response in the visual system (Wann, Rushton, & Mon-Williams, 1995).

Of course, one may be able to prevent such aftereffects altogether if VE systems entail no intersensory discordances, thereby making adaptation (and subsequent aftereffects) unnecessary. There are technological solutions to some of the display issues through the development of volumetric displays (McKenna & Zeltzer, 1992). Binocular aftereffects may also be reduced by removing stereoscopic depth (Rushton et al., 1994), but this also removes a valuable source of information for the user. Until the technological defects of most current VEs can be corrected, adaptation and aftereffects will be inevitable concomitants of their use. Welch (1997) suggested, however, that VE software and hardware may eventually improve to the point that there is little or nothing left in the VE to cause adaptation, and thus we might see the decline or perhaps elimination of VE aftereffects. Of course, there will need to be veridical movement to completely eliminate the need for adaptation. Conversely, Stoffregen, Bardy, Smart, and Pagulayan (in press) and DiZio and Lackner (1992) suggested that it will not be possible for VE technology to improve to the point that there is no requisite adaptation; they suggested that adaptation will always be necessary for any simulation of inertial motion of the user.

There is an alternative to the technological solution. If a VE does include discordances that trigger adaptation but *dual adaptation* (i.e., the ability to seamlessly transition between two disparate sensory environments) has been produced within the user and is complete, aftereffects should either not occur or be extremely short-lived (e.g., Welch, Bridgeman, Anand, & Browman, 1993). The concept of dual adaptation is that, as a result of repeated adaptation to a given VE and readaptation to the normal environment, users will eventually acquire the ability to move between the virtual and real environments with little or no interference (i.e., no aftereffects). This concept is critical to preflight adaptation training (e.g., Parker, Reschke, Ouyang, Arrott, & Lichtenberg, 1986), because astronauts must be adapted

[1]The AC/A is the accommodative convergence that is promoted by a given level of accommodation, whereas CA/C is the convergence accommodation that is promoted by a given level of convergence. Both result from the natural cross-links between the two systems and are measured by presenting only one stimulus (e.g., an accommodative target) while removing cues for the other stimulus (e.g., convergence).

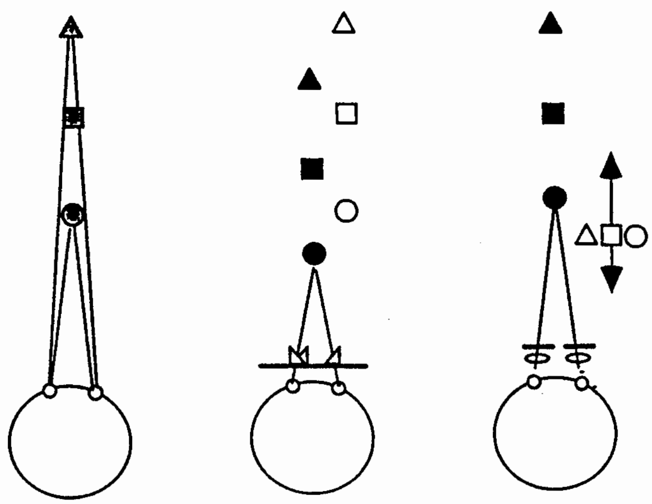

FIGURE 1 Mapping of vergence positions to accommodative state. In natural conditions, the stimuli to accommodation (empty symbols) and vergence (shaded symbols) are in accordance. If lens or prism power is induced then the stimuli become discordant but the degree of discordance is constant regardless of fixation point. In a generic stereoscopic display, the accommodation and vergence stimuli are disassociated and the degree of conflict varies with viewing distance, hence making simple adaptation difficult (from Wann & Mon-Williams, 1997).

to the altered gravitational environment to which they are traveling (e.g., the .38 g of Mars) as well as the environment in which they are currently spending most of their time (e.g., the 0 g of the Mars-bound spacecraft).

There is evidence of dual adaptation with astronauts. Comparison of responses from multi- and first-time astronauts indicate that veteran astronauts (i.e., those with more than one space flight) demonstrate less postflight alteration in head control strategies than participants on their first flights (Newman, Jackson, & Bloomberg, 1997; Paloski, Bloomberg, Reschke, & Harm, 1994; Paloski, Reschke, Doxey, & Black, 1992). Postflight behavioral differences between astronauts based on their experience level have been observed in tests of dynamic postural equilibrium control and jump landings. In these tests, inexperienced astronauts showed greater postflight decrement in postural stability than their more experienced counterparts. Such differences may be the result of many factors. However, they do indicate a prolonged retention of learned strategies in experienced astronauts that enables quicker adaptive transition from a microgravity to a terrestrial environment. The identification of a learned enhancement in the capacity for flexible motor responses to altered sensory input and its association with reduced decrement in postflight motor control suggests that preflight training regimes may be designed that promote development of motor response flexibility. This increased capability for motor response flexibility might aid in mitigating postflight motor disturbances. Similar techniques could be used to elicit adaptation to VE systems.

Although there is evidence for dual adaptation (e.g., Welch et al., 1993), so far it has not been experimentally demonstrated how to systematically generate complete dual adaptation or how to predict the possibility that any dual adaptation will be achieved. Aftereffects could be minimized or even eradicated if such strategies are identified, because any adaptation elicited by a VE system could be dissipated by dual adaptation. Thus, the identification of such adaptation strategies could prove highly beneficial to the advancement of VE technology.

Measuring Aftereffects

Systematic means of measuring and managing VE aftereffects would facilitate the development of technological or adaptive countermeasures. It is important for developers of VE systems to be able to determine if there will be aftereffects from the use of their systems and what percentage of the user population will be affected.

Based on work on simulators, sea conditions, and space sickness, there is general consensus on how to measure aftereffects from VE exposure, although there are many distinct forms of measurement apparatus used for this purpose. One form of measurement that is commonly used is subjective self-report of symptomatology after exposure. Another form is objective measurement of physiological adaptation of the vestibular, visual, and proprioceptive systems.

Subjective Measures of Aftereffects. From 80% to 95% of individuals exposed to a VE system report some level of postexposure symptomatology (Cobb et al., 1998; Kennedy & Stanney, 1997). Although the extent of the discomfort can be as slight as a headache, some 5% to 30% experience symptoms severe enough to cause them to discontinue VE exposure (DiZio & Lackner, 1997; Wilson, Nichols, & Ramsey, 1995). It is important to note that the user attrition rate tends to be related to user susceptibility, as well as system characteristics (e.g., stimulus strength). Thus, to determine the differential effect of user and system factors on symptomatology, it is important to determine the various drivers of cybersickness and to create a predictive model whereby cybersickness and aftereffects can be predicted.

The most commonly used tool to assess subjective symptomatology is the SSQ (Kennedy, Lane, et al., 1993), which was originally devised to evaluate aircraft simulator systems. This self-report questionnaire had its origins in the lists of symptoms reported by Sjoberg (1929), Tyler and Bard (1949), Chinn and Smith (1953), and McNally and Stuart (1942), as well as the studies of Wendt (reviewed in Wendt, 1968), the latter of whom attempted to assess the continuum of motion sickness symptoms by employing a 3-point scale. Wendt's scale was used to assess motion sickness symptomatology in which *vomiting* was rated highest, then *nausea without vomiting*, and finally *no symptoms*. Kennedy and Graybiel (1965) also used a self-report technique that incorporated participants' comments about the symptoms they experienced to compile a symptom checklist. These symptoms were combined to form a 5-point composite score that was used to assess symptoms experienced during slow rotation room studies (Kennedy & Graybiel, 1965; Kennedy, Tollhurst, & Graybiel, 1965). Symptoms covered in the questionnaire included: cerebral (e.g., headache), gastrointestinal (e.g., nausea, burping, emesis), psychological (e.g., anxiety, depression, apathy), and other less common characteristics of motion sickness such as fullness of the head. Today the SSQ consists of a checklist of 26 symptoms, each of which is designated in terms of degree of severity (*none, slight, moderate, severe*), with the highest possible total score being 303. A weighted scoring procedure is used to obtain a global index, known as the Total Severity (TS) score, which reflects the overall total discomfort level. The SSQ also provides scores on three subscales representing separable dimensions of simulator sickness (i.e., nausea, oculomotor disturbances, and disorientation). By means of these subscales cybersickness can be more fully characterized. A short derivative of the SSQ is the Short Symptoms Checklist, designed to allow monitoring of the course of symptoms during the time of VE participation (Nichols, Cobb, & Wilson, 1997).

Another subjective evaluation technique that has been used in the assessment of VE systems (DiZio & Lackner, 1997) is based on the diagnostic criteria of Graybiel, Wood, Miller, and Cramer (1968). With this technique, sickness is scored using a symptom checklist, which includes nausea, pallor, cold sweating, increased salivation, drowsiness, headache, flushing, and dizziness. A total malaise score is derived from the symptom checklist, with scores in the 8-to 15-point range indicating severe malaise. Thus, whereas the SSQ provides three subscales with which to characterize sickness, the Graybiel symptom checklist focuses on just the one malaise construct. Another difference is that the SSQ can be used in conditions in which participants fill out the questionnaire under field conditions without supervision, whereas the Malaise Checklist must always be done by a trained observer and is most often used under controlled laboratory conditions. The test–retest reliability of the Malaise Checklist is 0.91 (n = 21; P. A. DiZio, personal communication, December 1, 1997). The split-half reliability of the SSQ, adjusted for full-scale length, is 0.83 (n = 3,300 military aviation personnel; Kennedy, Drexler, Stanney, & Harm, 1997).

The three SSQ subscales fit nicely with theoretical descriptions of motion sickness (e.g., Money, 1970; Reason & Brand, 1975) and, for those who have personally experienced motion sickness, these three factors have obvious face validity. Furthermore, in an analysis of more than 1,000 simulator exposures, whereas the nausea subscale of the SSQ correlated highly (r = .88) with the Malaise Checklist, the correlations with the disorientation (r = .63) and oculomotor (r = .64) subscales were much lower. Thus, 77% of the variation in the Malaise score can be accounted for by the SSQ nausea score alone (uncorrected for reliability attenuation), whereas only approximately 40% can be accounted for by the SSQ disorientation and oculomotor subscales. This suggests that the SSQ provides information about other dimensions of sickness that is uniquely different from that provided by the Malaise Checklist. This additional information can be used to more fully assess the symptomatology being experienced by a user. It may even be possible that the distribution of the three SSQ subscales provides insight into the technological or individual factors leading to high levels of discomfort and could thus be used as a diagnostics tool.

Using the SSQ as the measure, Figure 2 shows the average TS scores for cybersickness, simulator sickness, and space sickness (Kennedy & Stanney, 1997). The average score for HMD-based VE systems is approximately 29 (with a range of 19–55) on the TS scale. In comparison, the average from eight U.S. Army and U.S. Navy Marine

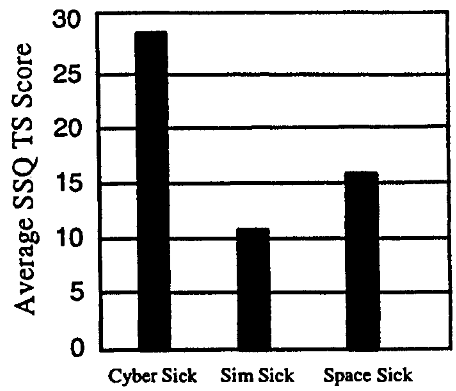

FIGURE 2 Total score of sickness.

Corps helicopter simulators is approximately 12 (with a range of 7–20). These results indicate the presence of substantially lower simulator sickness severity in helicopter flight trainers than in VE systems. Further, the space sickness TS displayed in Figure 2, which is based on the postflight reports of 85 astronauts, is between the average for simulator and VE exposures. It would appear that VE users report nearly two and a half times more sickness after exposure than do users of military flight simulators and nearly two times more than astronauts during space travel.

An examination of immediate postexposure profiles of VE systems using HMDs indicate that, on average, these systems tend to produce more disorientation (D) than neurovegative (N) symptoms and least of oculomotor-related (O) disturbances (see Figure 3). This means that users of these systems are more prone to experience dizziness, vertigo, general discomfort, increased salivation, sweating, and nausea, than they are to encounter headaches, eyestrain, or difficulty in focusing. Interestingly, this D > N > O profile does not match the profiles of other provocative environments (see Figure 3), including simulator sickness, which has an O > N > D profile, and space sickness, which has an N > D > O profile (Kennedy, Lane, et al., 1992). This VE profile is reliable, having been replicated with five different VE systems, using different HMDs. Because flight simulators and VEs are both visually interactive environments, one might expect their symptom profiles to match. Their diverse profiles indicate quite convincingly, however, that these systems differ substantially in the symptomatology that they produce. This may indicate that a new factor analysis is required to optimize the use of the SSQ for VE systems.

Objective Measures of Aftereffects. Although the SSQ allows for subjective self-report of symptomatology, recent results from VE studies indicate that it would be beneficial to supplement these reports with standardized and normalized objective measures of aftereffects. This is particularly important, because although sickness and objective measures of aftereffects are usually found to be statistically increased after exposure, correlations between these objective measures and subjective measures (i.e., both the SSQ and Malaise Checklist) have been found to be insignificant (Deisinger & Riedel, 1996; P. A. Dizio, personal communication, December 1, 1997; Kennedy, Stanney, et al., 1997). This implies that measuring sickness alone may not fully characterize what users are experiencing post-VE exposure. It

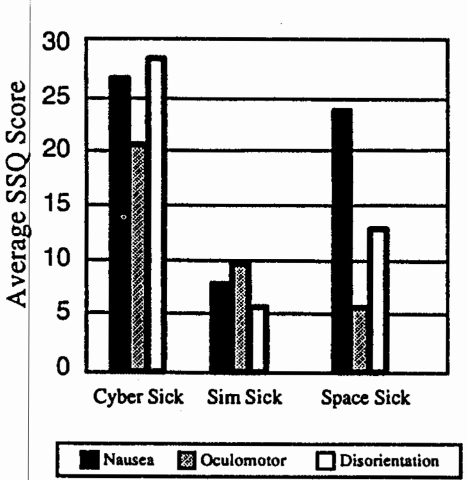

FIGURE 3 Spectral profiles of cyber, simulator, and space sickness.

is important to determine how serious aftereffects are and their related consequences for participants' well-being after VE exposure.

There have been a number of efforts to measure problematic adaptation to VE systems. For example, postural instability or unsteadiness can be related to postexposure driving safety (e.g., the Navy and Marine Corps instituted grounding policies after simulator flights several years ago; Kennedy et al., 1989). For this reason postural equilibrium has been proposed as an indexing system for identification of VE systems that have greater than normal aftereffects. Cobb (in press) evaluated a number of approaches to measuring postural stability after VE exposure and suggested that those based on sway magnetometry are most sensitive. Kennedy and Stanney (1996), using a tandem (heel-to-toe) posture, developed and validated such a measurement device to assess post-VE exposure postural instability. This approach, which measures instability of the head, may need to be extended to whole body measurement to increase its sensitivity and accuracy. DiZio and Lackner (1997) also measured postural instability after VE exposure, using a Kistler force platform and the standard Romberg posture. They found a fivefold increase in sway amplitude after only 15 min of VE exposure as compared to preexposure levels. These aftereffects dissipated exponentially to baseline and were no longer measurable 15 min after VE exposure. It may also be possible to measure postural instability during VE exposure and to determine the relative sequence of postural and subjective effects. Stoffregen and Smart (in press) measured postural sway during exposure to oscillating global optical flow and found increases in several parameters of postural motion prior to the onset of subjective symptoms of simulator sickness. This might permit development of objective measures that could be used to predict and prevent sickness online.

The fact that VE aftereffects involve disorientation and disruption of postural equilibrium implies that vestibular mechanisms are involved. The vestibular system also controls gaze reflexes, and it is interesting to note that rate of adaptation of the vestibulo-ocular reflex (VOR) has been suggested as a possible predictor of susceptibility to VE exposure (Draper, Prothero, & Viirre, 1997; Draper, Viirre, Furness, & Parker, 1997). Draper (1998), in a study examining virtual image scale-factor changes (0.5x, 1.0x, 2.0x magnification) and system delays (125, 250 msec), found that VOR gain adaptation occurs with 0.5x (15% average decrease) and 2.0x (6% average increase) image scale conditions. The introduction of the time delays to the 1.0x conditions resulted in significant VOR gain reductions (8.5% on average) and increases in phase lag (2.6° on average).

Standard clinical tests of vestibular function may be useful in characterizing individual susceptibility to VE aftereffects. A National Research Council (1992) committee reviewed the literature on vestibular and postural testing as it relates to clinical assessment. They evaluated existing and emerging tests and recommended the most useful and standardized procedures. The findings of this committee would be a good starting point for evaluation of the vestibular aftereffects of VE exposure (and also vestibular predictors of susceptibility to aftereffects).

Stanney, Kennedy, Drexler, and Harm (in press) have developed a means of measuring changes in the kinesthetic position sense (i.e., hand–eye coordination) due to VE exposure. An example of the implications of degraded hand–eye coordination was cited by Biocca, a University of North Carolina psychologist. He described what happened to one of his colleagues following 20 min of VE exposure:

> The [VE] device was built to show doctors how organs and muscles look inside the bodies they would be cutting open. She took off the headset and reached for a soft drink. Ordinarily one would just reach out, pick it up and raise it to the mouth. She picked it up and found that she was pouring soft drink into her eyes. (Strauss, 1995, p. A1)

In other cases, however, such aftereffects have not been found. Cobb et al. (1998) found no significant change in performance of fine and gross motor control tasks or of concentration tasks before and after VE participation, although participants did subjectively report increased difficulty afterward. There was, however, a significant underestimation of reach distances postparticipation. Clearly, such aftereffects need to be measured and managed appropriately. For example, although it is premature to institute regulatory restrictions, it is possible that similar "grounding" periods may be needed for physicians, as are needed for pilots, following exposure to a VE trainer and before they are permitted to perform surgery.

Modifications of post-VE exposure visual functioning have also been measured. These were based on clinical tests of vision, such as visual acuity, heterophoria, near point of convergence, and amplitude of accommodation (Howarth, 1996, in press; Howarth & Costello, 1996; Mon-Williams & Wann, in press; Mon-Williams et al., 1993; Mon-Williams, Wann, & Rushton, 1995b; Rushton, Mon-Williams, & Wann, 1994; Wann & Mon-Williams, 1997). These measures have also been cross-related to symptomatic reports and comparisons made across different display conditions (Howarth & Costello; Mon-Williams, Rushton, et al., 1995; Mon-Williams & Wann, in press).

Changes in EEG, salivary cortisol composition, and heart rate levels and variability have also been reported after immersion in VE systems (Ramsey, 1997; Ramsey & Wilson, 1998; Strickland & Chartier, 1997).

All of the aforementioned measurement approaches could be used both to determine if a user has adapted physiologically during VE exposure and to determine when the user's effects have dissipated (i.e., when recalibration of normative physiological functioning has been achieved). Other aftereffects that have yet to be measured in a VE system, but that have been encountered in simulator systems include (a) asthenopia (Ebenholtz, 1988); (b) illusory climbing and turning sensations and perceived inversions of the visual field (Kennedy et al., 1992); and (c) changes in dark focus of accommodation (Fowlkes, Kennedy, Hettinger, & Harm, 1993).

Aftereffects appear commonly and may be expected to increase as VE devices become more realistic and more frequently used. Thus, methods should be developed to measure and manage the adverse effects of VE exposure. To develop these methods, the following steps should be taken:

- Standardize procedures for objective measurement of aftereffects. If possible, online measurement approaches should be established that are integrated into VE systems (e.g., incorporate postural measurement into the HMD tracker).
- Product acceptance criteria and systems administration protocols for use by manufacturers need to be provided to assure that cybersickness and aftereffects will be minimized.

Prior to the identification of technological solutions or dual adaptation strategies, a means of managing aftereffects must be identified. If large aftereffects (or potential aftereffects) exist following VE exposure, the best way to get rid of them is to require participants who have just exited the VE to engage in the same activities performed within the VE. This should be done by providing users with the same stimulus as in the VE, but without the sensory rearrangement imposed by the VE. In this manner, users should be able to "unlearn" all of the adaptation they acquired in the VE in a relatively short period of time. This procedure should eliminate both the immediate and possible delayed aftereffects. Although there is no research directly relevant to this suggestion, there is indirect evidence based on adaptation to sensory rearrangement research (see Welch, 1978) to suggest its validity. Stanney (1996) is examining the feasibility of developing virtual environment readaptation mechanisms whose purpose is to facilitate recovery to normative conditions after exposure to an HMD-based VE system. This work will first identify the natural decay time course of aftereffects from VE exposure (i.e., 15, 30, 45, and 60 min) and then determine if certain types of activities can facilitate this readaptation process.

It is important to note that judging what level of comparability of sensory stimuli in and out of a VE is required to achieve the desired rate of adaptation and readaptation will depend on the activities performed and the precise nature of the VE system. For example, Lackner and DiZio (1994) investigated adaptation of reaching movements in two VEs that differ slightly in the way they perturb the arm to simulate an artificial gravity environment. The form and rate of adaptation and readaptation elicited when the arm was perturbed by contact forces from a force-feedback manipulandum differed from what was seen when the same pattern of forces was applied with noncontacting, inertial Coriolis forces. This emphasizes the need for research to understand basic sensorimotor mechanisms in order to avoid the alternative, which is a case-by-case evaluation of the conditions necessary to produce the desired adaptation.

Relation Between Aftereffects and Task Performance

The relation between aftereffects (i.e., cybersickness and adaptation) and human performance in VE systems is not fully understood. It is commonly observed that when users initially interact with VE systems they make movements that are relatively jerky and uncoordinated. James and Caird (1995) attributed this difficulty in moving easily about a VE to a lack of correlation between the visual scene provided by the HMD and the haptic experience (i.e., the relations between the visual scene and the felt arm and hand positions are not as they would be in the real world). It certainly also entails a lack of correlation between motor actions and visual feedback. These perceptual mismatches are thought to lead to physiological adaptations that engender aftereffects.

Motion sickness is a pervasive condition, with no specific task being more affected than another. In fact, it now appears that motion sickness (including cybersickness), although certainly quite unpleasant, can sometimes be ignored by the sufferer when he or she is confronted with tasks that must be performed. For example, astronauts experiencing space motion sickness in one study (Thornton, Moore, Pool, & Vanderploeg, 1987) showed no decrements in manual tracking or complex reaction times and performed their assigned operational tasks well. In other missions, however, one participant demonstrated a decrease in the Sternberg reaction time processing rate during space motion sickness (Thornton, Uri, & Moore, 1993), and two astronauts on a space shuttle mission who experienced mild motion sickness symptoms showed increased choice and decision reaction times associated with their experiencing these symptoms, whereas two other crew members with no symptoms showed no performance changes in space (Ratino, Repperger, Goodyear, Potor, & Rodriguez, 1988). The relative low rate of reported incidences of performance deficiencies associated with space motion sickness may result from a very high degree of astronaut selection, training, and motivation, which can compensate for motion sickness effects on performance in this group, relative to participants in ground-based studies. Alternatively, it may reflect the "right stuff" attitude and reluctance to report performance problems that may negatively impact the evaluation of the crew member and fitness for space mission duty.

An aspect of performance that is relevant to visual tasks in an HMD is the ability to view head-fixed targets while undergoing head motion (Guedry, Lentz, & Jell, 1979; Guedry, Lentz, Jell, & Norman, 1981). The vestibular reflex must be suppressed visually to read a display under such conditions. As anyone who tries to read in a car moving down a windy road will learn, this is a sickening and not altogether successful struggle. New tests of the ability to visually suppress vestibulo-ocular reflexes during head movement are being evaluated (Clark & Hopkins, 1997; Lee, Durnford, Crowley, & Rupert, 1997) and may prove to be useful in characterizing the aftereffects of VE exposure.

As people adapt their movements and visual functioning to effectively manipulate objects, move about, and so forth in the VE, their behavior becomes more fluid and controlled. This adaptation may be facilitated by streamlining the degrees of freedom through which VE users can move about the virtual world (Stanney &

Hash, in press). For example, McCauley and Sharkey (1992) suggested that during initial interaction, tasks requiring high rates of linear or rotational acceleration and extraordinary maneuvers (e.g., flying backward) should be avoided. Physically restraining individuals during motion has been shown to reduce motion sickness (Jones, 1997; Wilpizeski, Lowry, Contrucci, Green, & Goldman, 1985). Additional benefits have been derived by maintaining an HMD FOV of at least 150 × 60° covered by the lens system (which can be derived from tests; Deisinger & Riedel, 1996), so as to avoid too-frequent head movements and achieve higher levels of immersion. This contrasts with the deleterious effects of a large FOV in situations wherein head movements are a required part of the VE training regimen (cf. DiZio & Lackner, 1997).

DiZio and Lackner (1997) introduced a means of circumventing motion sickness for HMD-based VE systems that require head movements. This technique involves "greying out" or blanking the display above a threshold level of head velocity, which selectively eliminates the effect of visual update delays during head movements. In the absence of visual contrast, visual update delays are inconsequential. Blanking has been found to drastically reduce motion sickness and does not interfere with presence, predictably, because the blanking periods are so brief. Another technique that has been useful in easing user interaction, particularly the accuracy of locomotion activities, is to manipulate the degree of abstractness (e.g., polygonal vs. texture gradient; James & Caird, 1995).

Reducing the information content of a VE, however, may have implications for task performance. Reducing the spatial frequency content of the display and degrading the optic flow may reduce cybersickness, but may also undermine the user's ability to detect direction of heading from optic flow (Warren & Hannon, 1988) or to steer effectively on the basis of higher derivatives of the optic flow field (Wann, Rushton, & Lee, 1995). The removal of stereoscopic depth cues has also been discussed as a means of avoiding some visual aftereffects, but it can also be demonstrated that this will affect the user's ability to make precise judgments of impeding arrival or collision in VE settings (Heuer, 1993; Wann, 1996; Wann & Rushton, 1995). Any changes in the information content have to be balanced against removing the information that users would ordinarily rely on for accurate judgments. The classes of visual information implicated in producing aftereffects (motion parallax, optic flow, binocular stimuli) are also those critical to precise control (see Figure 4 or reference Wann & Mon-Williams, 1996). For example, in one study visual aftereffects with a desktop stereo display could only be produced when the participants were required to precisely follow targets in depth for an extended period (Mon-Williams & Wann, in press). Hence, there is an uneasy conflict between VE users striving for optimal performance and the incidence of aftereffects.

Regardless of the causes of adaptation to VEs, the aftereffects of this adaptation probably include changes in oculomotor control, hand–eye coordination, postural control, loss of visual position constancy, and changes in proprioception (Welch, 1978). Obviously, then, any postexposure performance tasks whose accurate performance require normal oculomotor control, hand–eye coordination, and so forth will be adversely affected by these aftereffects. Clearly, the tasks that are almost guaranteed to be disrupted are the ones in which the user was engaged during the VE experience.

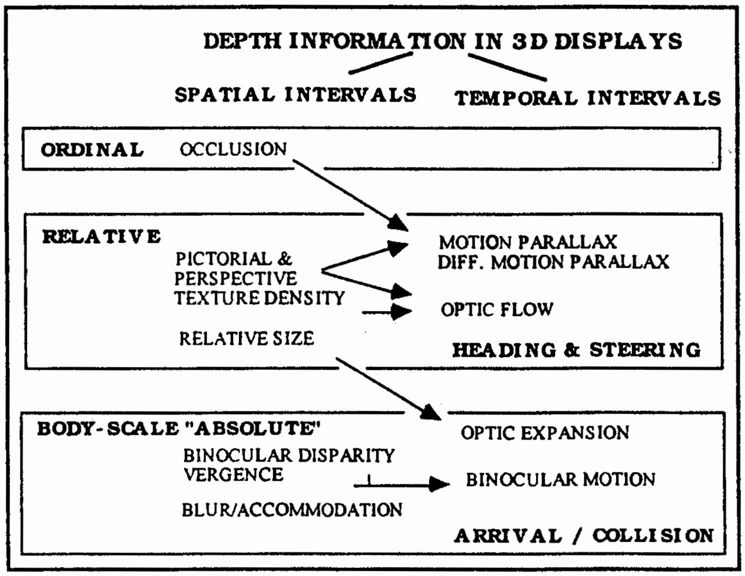

FIGURE 4 Sources of information supporting judgments of depth and motion in depth. The arrows indicate how the information changes when a static display (spatial intervals) is set in motion (temporal intervals). Specific classes of information can be identified as supporting judgments of heading, steering, and arrival. Reprinted from *International Journal of Human Computer Studies, 44,* J. P. Wann & M. Mon-Williams, "What Does Virtual Reality NEED?: Human Factors Issues in the Design of 3D Computer Environments," pp. 829–847. Copyright 1996, by permission of the publisher, Academic Press Limited, London.

3.2. Sense of Presence

The efficacy of a VE has often been linked to the sense of presence reported by its users. Important research questions concerning the sense of presence in VEs include: (a) how presence should be defined, (b) how it should be measured, (c) what are its controlling variables and their relative weighting, (d) what is its relation to task performance, and (e) should VEs be deliberately designed to induce a strong sense of presence?

Defining Sense of Presence

There is currently no clear consensus on how to define sense of presence. It has been described as a perceptual flow requiring directed attention and is based on the interaction of sensory stimulation, environmental factors, and internal tendencies (Singer & Witmer, 1997). Simply stated, the sense of presence may be defined as the subjective experience of being in one place or environment even when one is physically located in another (Witmer & Singer, in press). For VEs, presence means experiencing oneself as being in the computer-generated environment rather than in one's actual physical location. Humans experience varying degrees of presence in a physical locale, typically dividing attention between the physical world and the mental world (overt and covert memories, cognitive activities, etc.; Singer & Witmer, 1997). Sense of presence may be driven by the vividness of an experience (i.e., the sensorial richness) and the level of interactivity or degree to which a participant can manipulate objects and move about in a virtual world (Steuer, 1992). By means of these latter factors, an operational definition of sense of presence could be established that would assist in standardizing the approach to its measurement and use as a predictive variable. A desirable goal would be to develop an operational definition of presence with objective measures that could assist in determining the appropriate level of presence required for a given set of task conditions.

How sharply users focus their attention on the VE partially determines the extent to which they will become involved in that environment and how much subjective presence they will experience and report (Witmer & Singer, in press). Selective attention is the tendency to focus on specific information that is meaningful and of particular interest to the individual. Experiencing presence in a VE requires focusing on a meaningfully coherent set of stimuli (i.e., the VE) to the exclusion of unrelated stimuli (i.e., the physical place in which the VE is located). This can occur both for VEs (feeling that one is in the sensory world created by the computer) and teleoperator systems (feeling that one is located at the distant site of the "telerobot"). The latter experience is often referred to as "telepresence." This argument for the importance of attention in sense of presence is similar to McGreevy's (1992) concept that the experience of presence is based on attention to the continuity, connectedness, and coherence of the stimulus flow. The coherence of the VE thus facilitates the focus of attention without forcing it. This concept of enabling without force distinguishes the experience of presence from the factors that support presence (i.e., involvement and immersion).

Both involvement and immersion are necessary for experiencing presence, but neither is sufficient (Witmer & Singer, in press). *Involvement* is a psychological state experienced as a consequence of focusing one's energy and attention on a coherent set of stimuli or meaningfully related activities and events. Involvement depends on the significance or meaning that the individual attaches to stimuli, activities, or events. Witmer and Singer (in press) suggested that as users focus more attention on the VE stimuli, they should become more involved in the VE experience, leading to increased presence. *Immersion* is defined as a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences. Factors found to increase immersion include isolation from the physical environment, inclusion in the situation, being allowed to use one's natural mode of interaction and control, and the presence of stimuli that support the perception of self-movement. High levels of immersion depend on the availability and perception of an encompassing stimulus stream. Witmer and Singer (in press) suggested that a valid measure of presence should address factors that influence both involvement and immersion. It should also be noted, however, that although the underlying constructs of involvement and immersion may be distinct, increased levels of involvement influence users to experience more immersion and vice versa.

J. Maida (personal communication, November 25, 1997) suggested that the sense of presence can have another, less abstract facet called "sense of engagement." Maida suggested that this construct is related to (a) the level of "user motivated" interaction with the VE system; (b) the level of reaction by the VE system to user actions (Hansen & Haas, 1998), which should be very robust (e.g., if users make quick or sudden moves, the system must respond correctly and quickly with no perceivable lag or distortion of motion; Adelstein, Johnston, & Ellis, 1996); and (c) the motivation of the user to continue to "play the game" or maintain involvement in the VE interaction, which may be independent of realism (Hansen & Haas, 1998). The latter can be exemplified by considering avid users of video games in which visual realism is not a factor. In such cases, other factors, such as the interaction with the game or the story, keep the users engaged. In addition, books, which have very limited visual realism, effectively engage our minds and imagination.

Measuring Sense of Presence

Although the concept of presence has been widely discussed, few researchers have attempted to systematically measure it and relate it to possible contributing factors. Currently there is limited understanding of whether sense of presence is simply an epiphenomenon of good human–machine communication or potentially even a distraction (Ellis, 1996). A measure of presence could potentially assist developers of VE systems in enhancing the design of the human–VE interface, assuming that there is agreement that this would actually serve this purpose. In addition, by addressing the issue of how to measure presence, greater understanding of the factors that drive this phenomenon may result. Measures of presence should be repeatable, reliable, robust, and sensibly correlated with measurable characteristics of the VE. Of course we also need to be aware that presence may be no more unitary than situation awareness or emotion, and, as such, the quest for a single index that tells us "how much" may never be achieved. Nevertheless, there are two general means of measuring the sense of presence in a VE: subjective reporting and objective measurement.

Subjective Measures of Presence. Subjective assessment of VE systems may prove particularly useful in the early evaluation and exploration of these systems. Ellis (1996) obtained empirical evidence to suggest that subjective responses to the characteristics of VE systems may meet proposed criteria for explanatory constructs, including repeatability, reliability, and robustness. Witmer and Singer (in press) have data from several experiments that show their subjective measure of presence is reliable and indications of meaningful relations with learning, aftereffects, and performance. Subjective measures of presence include such psychological measuring devices as (a) rating scales (e.g., "On a 1–10 scale, rate the amount of presence this VE produces for you") or equivalence classes; (b) the method of paired comparisons (e.g., "Which of these two VEs produces the greater amount of presence for you?"); and (c) cross-modality matching (CMM; e.g., "Make this light as bright as the strength of the presence you experienced in this VE"; Welch, 1997).

• Rating Scales: Subjective evaluation scales, such as that created by Cooper and Harper (1969), have been used to assess VEs (Rosenburg & Adelstein, 1993; Slater, Usoh, & Steed, 1994; Witmer & Singer, in press). Slater et al. (1994) measured presence as a function of a sense of (a) "being there," (b) being more "real or present" than everyday reality, and (c) perceiving the VE as a "locality" or a "place" that was visited rather than merely seen. Witmer and Singer (in press) developed the Presence Questionnaire (PQ), which measures presence along three subscales: (a) involvement and control, (b) naturalness, and (c) interface quality. The reliability, validity, and utility of the PQ have been iteratively investigated. The results of these studies indicate that the PQ is a reliable scale, and presence, as measured by the PQ, is a valid construct. Although subjective ratings scales are effective means of assessing presence, it is important to note that such scales should be used judiciously due to inconsistencies across different raters or rating situations (Ellis, 1996). Different users may apply these scales differently, and thus a means of calibrating individual differences may be required to control for bias (Mendal & Sheridan, 1989).

• Equivalence Classes: Subjective or other synthetic constructs, such as workload, presence, or intelligence, are not operationally related to physical variables. They are occasionally proposed as explanations for human performance in situations of interest to human factors researchers. For these constructs to have explanatory validity they should allow the establishment of empirically demonstrated equivalence classes (Ellis, 1996). Such a demonstration requires that when the factors that influence the construct cause it to vary, there is a corresponding change in performance. It also requires that a variation that does not cause the construct to change should have no effect on the performance that the construct is thought to explain. Thus, equivalence classes have utility for assessing both changes and constancies in presence. This dual relation arises when the response surface of the synthetic measure and that of the performance variable are geometrically similar (see Ellis, 1996).

• Method of Paired Comparisons: Schloerb (1995), among others, proposed an intriguing paired-comparisons procedure in which the observers' task is to distinguish between a real-world scene and a VE simulating that scene. Thus, if users are unable to detect a difference between the two experiences, one can reasonably conclude that their sense of presence in the VE is just as strong as in the real-life scene (i.e., maximal). This might be termed a "virtual reality Turing Test," wherein the goal is not to distinguish artificial intelligence from a sentient person, but rather to distinguish artificial reality from organic reality (Welch, 1997). Because with present VE technology it is very unlikely that observers will mistake a given VE for a real one, a method for quantifying the presence produced by this VE is to systematically degrade perception of the real scene until the observer can no longer differentiate it from the virtual one, with the amount of degradation required to reach this level serving as a measure of the degree of presence. This application of paired comparisons is likely to be extremely sensitive to very small differences between a real scene and a VE. The size of the difference that is detectable (known as the *just noticeable difference*), however, will depend on the aspect of the control stimulus (viz. the real scene) that is degraded. It is likely that individuals will be far more sensitive to degradation along some dimensions (e.g., increasing lag between head movement and scene movement) than along others (e.g., degradation of stereo sound). Furthermore, in many cases it would be very difficult to degrade all aspects of the real scene to precisely match the VE. Even if a precise match could be accomplished, obtaining a single quantitative measure of the required degradation would be an extremely complex process, if possible at all.

The primary advantage of the paired comparisons method is that it does not require investigators to explain to their participants what they mean by presence or even to introduce the term at all. This is desirable because the act of carefully defining this concept for participants may create a situation in which the investigators guarantee confirmation of their hypothesis, particularly if their definition mentions or even implies the variables that they will be manipulating. For example, imagine an investigator who defines presence to participants as "the feeling of being immersed in the environment." If the experimental hypothesis is that wearing an HMD will increase the sense of presence, it is obvious that the only possible outcome of this study is to confirm this prediction, which would represent a self-fulfilling prophecy.

• CMM: Because of the broad success with CMM for intensive sensory dimensions, particularly with those that do not lend themselves easily to verbal scaling, we think that CMM might be a useful psychophysical technique to apply to the scaling of presence.

The scaling of sensory experiences, or *psychophysics*, provided psychology with its original experimental basis in the late 19th century. A half a century later, Stevens's work (1951) can be credited with providing a very strong heuristic push to the modern field of psychophysics when he posited that physical intensity can be translated into psychophysical scales, and the general expression of this relation is that the subjective perception grows as a power function of the stimulus (but see Guilford, 1932). Currently, there is a huge literature on single-modality psychophysical scaling and a burgeoning literature on CMM (Luce & Krumhansl, 1988).

In sensory psychophysics, for the single modality case, Stevens and Guirao (1963) suggested the possibility of a single sensory dimension of intensity, although no one has actually pushed these studies through in the detail necessary to know whether the various intensity scales exhibit a structure similar to the scales of physics or is it just how people use numbers. Sensory psychophysical scales are universally used and accepted in experimental psychology, and they tend to be reliable and stable. The psychophysical powers or exponents, however, can be shifted by as much as 300% differences (King & Lockhead, 1981), and early data demonstrated that the exponents are affected by a variety of experimental manipulations (Poulton, 1968). In addition, if there are consistent individual differences in the exponents and if they are interrelated in systematic ways to each other or to other criteria, then the exponents may be highly correlated over participants (see references in Rule & Markley, 1971). Although the individual differences have more to do with the use of numbers in responding than with differences in the sensory systems, Reason (1968) demonstrated that individual differences in the exponent of spiral aftereffects and loudness estimation were predictive of motion sickness susceptibility. In sum, there is considerable consistency in psychophysical scaling, and it remains one of the most powerful ways to collect human data.

A paradigmatic variation of the single modality psychophysical scale, alluded to previously, rests with a series of studies conducted on CMM (Luce & Krumhansl, 1988). In these examples, a particular modality becomes the stimulus and another modality becomes the expression by the participant. In CMM, Psychological Test 1 and Psychological Test 2 are two intensive physical measures, and the corresponding subjective scales are each monotonic with stimulus energy. These scales can ordinarily be expressed according to the general form of Stevens's power law (Stevens, 1951), in which case CMM can be accomplished empirically. Not only is a power function predicted, but its exponent is uniquely determined. As an example of the generalizability of the law, a third modality could also be employed.

Luce and Krumhansl (1988) reported that in Stevens's work on CMM, he used the geometric mean as his estimate of the symmetrical exponent relating dimension *i* to *j*. Using this exponent to make predictions, he obtained an average absolute error of 4% for one set of 9 modalities, each matched to handgrip; and 11% for another of 10 modalities matched to loudness. Baird, Green, and Luce (1980), working with extensive data for 3 participants, were considerably less successful. Daning's (1983) study of cross-modal matches involving four modalities was more favorable. Nearly every intensive dimension has been scaled and although the exponents in the power function range from approximately .02 to 4.0, the power law remains remarkably robust for averaged data, although methodological issues need further study.

A specific example may be clearer: A signal (say, luminance or presence) is presented in one modality and is matched by one in another modality (say, the pressure of a finger on a transducer or adjustment of line length; Stevens & Guirao, 1963). Then, in the previous example, a participant's task would be to exert pressure on the transducer as strongly as the light was bright or the presence was felt. Another example would be after a participant has interacted with a given VE, he or she is instructed to control the intensity of a sound until it matches the amount of presence (previously defined in some manner to the participant) experienced in that VE. The result will be that VEs that induce different degrees of presence will elicit corresponding differences in the intensity of the sound the participant uses to "describe" them.

Although there are methodological difficulties with the cross-modality approach as listed here (e.g., whether estimation followed by production can predict cross-modal function, individual differences, etc.), nonetheless, we believe that as a quantitative metric CMM holds promise for the measurement of elusive, signal intensity, continua (Stevens, 1951), and, in particular, we believe it could be applied for the scaling of presence.

Objective Measures of Presence. Humans routinely experience physiological responses to stimuli in the real world. Similarly, as the sense of presence in a VE increases, corresponding changes should occur in physiological parameters. For example, if a VE user sees a leaping virtual tiger and involuntarily flinches, screams, and registers a sharp increase in heart rate, it is reasonable to conclude that he or she experienced a strong sense of presence. Held and Durlach (as cited in Sheridan, 1992) first described this notion of testing the user's response to unexpected or threatening stimuli in 1987. Measures of presence could include both neurophysiological responses and reflexive motor acts. Physiometric measures to events in a

VE could include posture, muscular tension, cardiovascular behavior, and ocular responses (Barfield & Weghorst, 1993). For example, heart rate and evoked cortical response to the optical looming of objects or events in a VE could be an indication of the presence they engender. Wilson, Nichols, and Haldane (1997) used reaction to "startle" measures related to an unexpected event within the VE, and awareness of background music, to assess presence in a direct fashion. They also related the results to items from two presence questionnaires and believe that the startle response at least has merit as a candidate measure.

Objective measures will be most useful when they are tailored to the experiences participants are intended to have in a VE system. For example, Cohn, DiZio, and Lackner (1996, 1997) demonstrated a useful automatic motor response that is a measure of presence in a VE meant to induce a sense of body rotation. Participants who are physically rotating but who feel stationary make errors when pointing to targets. The paths and endpoints of their movements are deviated in the direction of the transient inertial Coriolis forces generated by their arm movements. By contrast, participants who reach while voluntarily turning their torso reach accurately even though large Coriolis forces are generated by their arm movements. This pattern suggests that the nervous system, in generating motor plans for reaching movements, takes into account whether the body is rotating and automatically includes forces counter to the expected Coriolis forces. If so, stationary participants who are experiencing virtual self-rotation should make reaching errors when pointing to a target. These errors should be in the direction opposite the Coriolis forces their arm movements would generate if they were actually rotating. The existence of such compensation was demonstrated by having participants reach while they experienced compelling virtual self-rotation and displacement induced by viewing rotation of a complex, natural visual scene in an HMD. The reaching movements of these participants were in fact deviated opposite in direction to the Coriolis forces that would have been generated during actual rotary displacement. By contrast, participants who viewed a simple pattern of rotating stripes experienced virtual self-rotation but, paradoxically, no displacement in the virtual world. Their reaching movements were not deviated in a way that related to expected Coriolis forces. In other words, the motor system was attuned to the high sense of presence provided by the natural scene versus the low presence engendered by the stripes. Gathering context-specific examples of this sort may help in devising a more general set of objective measures.

A drawback to objective measures is that they tend to be "all-or-none" and, even when they are not binary, their quantitative relation to presence may be unclear. It seems likely that both subjective and objective tools will be required for the comprehensive measurement and understanding of the sense of presence.

The Current State of Presence Measures. There is currently no consensus on how to measure presence. Without such a consensus, it is difficult to compare presence among participatory groups to assess the relative efficacy of different VE systems. In addition, when subjective presence measures are employed there will always be the concern of interrater reliability and the need for calibration among users.

Controlling the Variables That Influence Presence

In recent years, a large number of controlling variables for presence have been suggested and many experimentally tested (e.g., Heeter, 1992). Among these are ease of interaction, degree of user-initiated control, pictorial realism, length of exposure, social factors, and system factors.

1. Ease of interaction: Weghorst and Bellinghurst (1993) manipulated the design of VE systems through the degree of abstractness of objects, as well as the use of a ground plane and other spatial landmarks. They found that designs that eased the interaction were most predictive of the sense of presence in the VE. This suggests that if VE interaction can be streamlined, interactive fidelity or presence may be enhanced.
2. User-initiated control: Witmer and Singer (1994) suggested that the more control a user has over their actions in a VE, the higher the ensuing sense of presence. They stated that this control factor is driven by the immediacy of the system response and appropriateness of user-initiated actions, as well as the naturalness of the mode of control. Similarly, Welch, Blackmon, Liu, Mellers, and Stark (1996) conducted a study that found that sense of presence was higher for VE users who were in control of their own actions in the VE as compared to passive observers. This suggests that if users are provided with a high level of user-initiated control, presence may be increased.
3. Pictorial realism: Pictorial realism enhances the sense of presence in VE systems (Welch et al., 1996). Witmer and Singer (1994) suggested that this realism is based on the connectedness, continuity, consistency, and meaningfulness of the perceptual stimuli presented to users of VE systems. Nichols, Haldane, and Wilson (1997) found that of all subjective responses to a VE, the feeling of apparent depth was most closely associated with sense of presence, with VEs appearing to be very "flat" providing the least presence.
4. Length of exposure: The amount of time spent in a VE may influence sense of presence, although it is unknown what that effect is. Extended exposure may increase presence because it enhances other factors thought to be related to presence, including the amount of practice with VE tasks, the familiarity with the VE, and the level of sensorial adaptation to the intersensory and sensorimotor discordances presented by the VE (Welch et al., 1996). Yet, if adverse effects, such as cybersickness, intensify during prolonged VE exposure (Kennedy et al., in press), then exposure and presence could be negatively related. Thus, it is uncertain whether long-duration exposure will enhance presence by engendering familiarity or reduce presence due to adverse side effects.
5. Social factors: There is growing interest in the social presence generated by the existence of virtual actors in the VE (Heeter, 1992; Steuer, 1992). Welch et al. (1996) suggested that sense of presence may increase with the existence of other individuals in the VE and the extent to which these other individuals interact with the primary user.
6. System factors: Technological factors such as the number of sensory modalities stimulated by the VE system (Heeter, 1992) and the use of head tracking and

stereoscopic cues (Hendrix & Barfield, 1996) have been suggested to enhance sense of presence. Other system factors, such as response latency (i.e., the time between user action and VE system feedback; Ellis, Dorighi, Menges, Adelstein, & Jacoby, 1997) and limited FOV (Prothero & Hoffman, 1995) may degrade sense of presence. Factors that degrade pictorial realism, such as delay of visual feedback, have also been found to degrade sense of presence (Welch et al., 1996). In addition, the display medium may affect sense of presence. In a comparison of HMDs, monitors, and screen-based projections, the screen-based projections were found to produce the greatest immersion in inexperienced users (Deisinger, Cruz-Neira, Riedel, & Symanzik, 1997). The monitor was perceived as the least immersive display. The HMD was criticized because of low resolution, blurred images (caused by the lenses), and cumbersome cables. Participants noted that they preferred the screen-based projection because it was perceived as the most natural display medium.

In most of these studies the resulting relation between presence and human performance was not explored. One important issue is this: Although a high level of streamlined interaction controlled by the VE user, pictorial realism, and social interaction, as well as optimized system factors, may increase sense of presence, will they also lead to enhanced human performance? By exploring the relations between these factors, sense of presence, and human performance, a better understanding of how to design VE systems should result.

Although the naturalness of the interaction, pictorial realism, and social and system factors are thought to affect the perceived level of presence, precisely how these factors combine and interact is unclear (Witmer & Singer, in press). Thus, of potential importance to designers of VE systems is an understanding of the relative weighting of these variables (Welch, 1997). For example, it would be useful to know if changes in cathode ray tube resolution have less of an impact on presence than delays in visual feedback or if a high level of user-initiated control is more essential than the ease of interaction. Determining such weights is not easy, however, because their assignment depends heavily on the levels of the variables examined in a given experiment and on the nature of the designated VE task. One such comparative study by Welch et al. (1996) found that pictorial realism enhances the perceived sense of presence in VE systems, although not nearly as much as the level of user-initiated control provided to users.

Relation Between Presence and Task Performance

The potential efficacy of VEs for training to perform real-world tasks is generally attributed to the level of presence provided by the VE system (Fontaine, 1992; Sheridan, 1992; Zeltzer, 1992). The ultimate VE is envisioned as one that is rendered much as the physical world, with visual, auditory, and haptic stimuli impinging on the human senses in a veridical manner. The reality is, however, that due to current technological limitations (Kalawsky, 1993) such a replica is not readily achievable nor may it be necessary for effective human performance due to the capabilities and limitations of the human perceptual system (Card, Moran, & Newell, 1983). Although sense of presence may not be necessary for effective human performance in

Should VEs Be Deliberately Designed to Induce a Strong Sense of Presence?

Although it is commonly thought that performance in a VE that provides a high degree of presence is likely to be better than a VE in which presence is low, there is little systematic research available to substantiate such a claim. By developing an understanding of the factors that drive presence, their interrelations, and how they relate to human performance and aftereffects, a set of design principles could be specified that should lead to enhanced human performance in VE systems. Prior to establishing such an understanding, however, it is ill-advised to unequivocally state that designers of VE systems should directly pursue designs that engender a high level of presence. Even if it is clearly and pervasively demonstrated that presence influences performance, its effect may not always be beneficial. Ellis (1996) provided two examples in which analysis of the desired causal control between system and user determined that the optimal sensorimotor transformations required by the task would be achieved by placing the user outside of (exocentric view) rather than the more "natural" position of being immersed within (egocentric perspective) the VE. Thus, there are two reasons it might be counterproductive for VE designers (with the exception of those in the entertainment industry) to establish a maximal sense of presence as a primary goal of their creations (Welch, 1997): First, it is possible that presence is simply an epiphenomenon of improved VEs and, second, even if there is a causal association between presence and performance, it may be a negative one. Witmer and Singer (in press), on the other hand, suggested that many of the same factors that increase presence are also instrumental in promoting learning and performance. Thus, other factors being equal, they believe VEs to be used for entertainment or for training should be designed to induce high levels of presence for certain tasks.

3.3. The Relation Between Aftereffects and Presence

Possible associations between presence and aftereffects may aid investigation into how to more effectively design the human–VE interface. One possible relation between presence and aftereffects is as follows (Welch, 1997): It has been hypothesized that the more veridical a VE recreates the physical world and the observer's sensory–motor relationship to it, the stronger the sense of presence and the less the aftereffects. Thus, in the ideal case, in which the VE involves no intersensory discrepancies whatsoever, there will be (a) nothing to which to adapt (and therefore no postexposure aftereffects), and (b) a strong sense of presence. If, as is more likely, a VE creates an imperfect version of real-world experiences and initiates an adaptive process to compensate for these imperfections, users will have little or no initial problem discriminating it from the real world (i.e., will experience less than maximal presence) and will reveal a postexposure aftereffect as a result of this adaptation. In the latter case, the strength of the initial sense of presence in a VE will be negatively correlated with the aftereffects produced by it. There is some empirical evidence to support this relation; Witmer and Singer (in press) and Singer et al. (1997) both reported a negative relation between sickness (as measured by the SSQ; Kennedy, Lane, et al., 1993) and presence (as measured by the PQ), although this relation was

not always significant. There may be evidence to refute this prediction as well. Wilson, Nichols, and Haldane (1997) tentatively reported a positive relation between sickness (as measured by a Short Symptom Checklist; Nichols, Cobb, & Wilson, 1997) and presence (as assessed by a subjective questionnaire, secondary task, and observational measures). One should, however, note the different measurement tools that were used, a fact that may have contributed to the conflicting nature of the results. In other experiments, using the PQ of Witmer and Singer (in press), Nichols, Haldane, and Wilson (1997) found results that suggest that sickness in the VE may detract from feelings of presence, especially as represented by the quality of the interface; presence measures were also strongly correlated with the enjoyment derived from the experience.

On the other hand, substantial adaptation to a VE may produce a strong sense of presence, which suggests a second prediction (Welch, 1997): The greater the aftereffects from a VE, the greater the increase in presence over the period of exposure to that VE. This hypothesis is based on the assumption that sizable VE aftereffects are the result of sizable VE adaptation. With this adaptation, observers will perceive much less of the intersensory discordances that initiated the adaptive process early on and which, at that time, mitigated against a strong sense of presence.

Finally, there is the possibility that aftereffects and presence are both correlated (either positively or negatively) with a third factor or variable (e.g., vection) such that changes in one do initiate changes in the other but solely via the intervening factor, and thus there is no direct connection between them (Nichols, Haldane, et al., 1997). For example, Hettinger and Riccio (1992) suggested that vection might be a necessary precondition of simulator sickness, independent of presence.

4. RESULTS

In this section results from the 16 questionnaire respondents obtained at the special session are presented. The distribution of responses per institutional type is indicated in Table 1. One research respondent was also involved in decision making and policy establishment. The questionnaire responses were collected at the end of the round-table discussion and a summary (by question) is presented in the following sections.

4.1. State of Scientific Knowledge

In general, the respondents felt that currently there is insufficient knowledge available to facilitate the effective and safe use of VE technology (see Table 2). The issues in Table 2 are presented in descending order of importance.

Table 1: Questionnaire Respondents

Research and academia	15
Industry	1
Decision maker or policymaker	1[a]
Total	16

[a]One respondent was both a researcher and a decision maker.

Table 2: State of Scientific Knowledge (in Order of Decreasing Importance)

1. Without a better understanding of human adaptation to VEs, cybersickness cannot be overcome and potentially dangerous aftereffects cannot be eradicated. Both of these problems greatly restrict the effective use of VE technology.
   - Lack of codevelopment between VE software and hardware leads to greater sensory discordance problems, thus engendering higher levels of initial cybersickness, as well as need for more adaptation and resulting substantial aftereffects.
     - ⇒ As long as aftereffects exist, there is a need to improve general populace awareness of the potential dangers and adverse effects of VE technology.
2. Research on transfer to real tasks is virtually absent. Thus, there is a lack of understanding of which applications are appropriate for VE technology. There is a need for basic task-performance assessment to realize effective use of VE technology.
   - Little is known about the interrelations among aftereffects, sense of presence, and task performance during and after VE use.
3. Lack of VE design guidelines to ensure ease of use.
4. For very limited applications, and given sufficient computing power, effective VE applications can be developed. However, their safety is not guaranteed.

Note. VE = virtual environment.

Overall, the most critical issue is the need to ground technological advances in a fundamental understanding of how these advances affect the human sensory or perceptual system. In particular, there is a dearth of information to fully characterize human adaptation (both plasticity and its consequences in aftereffects) with respect to VE systems. There is also a need for codevelopment of VE hardware and software so that they are better integrated, thereby minimizing the sensory discordances that lead to cybersickness and the necessity for adaptation. There is a need to educate the general populace about these concerns so they can self-regulate their usage of VE systems.

The next area identified by the respondents as one lacking in scientific knowledge is the determination of the most appropriate application areas for VE technology. Technology is currently driving VE use rather than specifying where this technology can be used to meet specific task goals. Thus, there is a limited understanding of how to apply VE technology to best meet training and performance requirements. To resolve this issue, extensive research is needed involving basic human performance assessment, leading to a task taxonomy that can be used to guide the effective use of VE technology.

Also unavailable are guidelines that can be used to optimize the design of the human–VE interface. Without such guidelines, ease-of-use issues (i.e., movement and object manipulation), as well as usability concerns (i.e., cybersickness) arise that limit the effective use of VE technology.

Finally, for very limited applications (e.g., those that keep frame rate high for limited but rich visual databases, those that involve tasks that do not require interactive manipulation of virtual objects, and those that minimize personal movement in crowded environments) and with adequate computing power the current state of knowledge is adequate to overcome issues related to cybersickness. This does not, however, guarantee that these systems are free from aftereffects.

4.2. Technological Impediments

The respondents identified the need for users to adapt to the technological shortcomings of the VE system (e.g., low resolution, small FOV, optical aberrations, latencies) as the most significant impediment to the effective use of VE technology (see Table 3). In systems that require adaptation, users may experience cybersickness until they have adapted and, more importantly, users may be maladapted to the real world (because of the aftereffects) once interaction with the VE has concluded. To resolve this issue an understanding of human context-specific adaptation in perception and cognition must be developed. Currently, little is known about how sensory systems respond in VE. Considerable knowledge is available in some areas of physiology (e.g., visual functioning), and this knowledge could be used to study VE effects. A better understanding of past simulator systems as compared to VE systems may also help discover means of overcoming technological shortcomings. More interaction between research institutions and industry in the design and integration of VE hardware and software could minimize the need for human adaptation. In addition, the advancement of VE technology may be hindered by the lack of awareness among the general populace that VE systems can create significant illness and aftereffects.

The second most critical impediment to the advancement of VE technology is the state of the technology itself. Currently the technology is too expensive, migration paths are too difficult, and there are only a few commercial systems available. The systems that are available generally have a limited FOV with inadequate resolution. Techniques for complex interaction and manipulation of objects in VE are lacking. In addition, there are problems in rendering complex and representative visual databases while maintaining sufficient update rates.

Another impediment is a lack of understanding of the important component factors of the VE experience itself and their interactions. Indeed, little is understood about such phenomenon in the real world. Current developers of VE systems have little guidance on how to elicit the intended effect and user performance in their designs. Wilson (1997) did report a framework to enable potential VE users to identify critical task attributes, specify VE system design parameters, guide VE development, and subsequently undertake evaluation of the VE, its effects, and its effectiveness.

4.3. Role of National Institutions

Interest in VE technology is so widespread that the U.S. government asked the National Research Council on two recent occasions to identify U.S. VE research priorities and coordination requirements (Chien & Jenkins, 1994; Durlach & Mavor, 1995). In the United Kingdom, the EPSRC (1995) has identified "Human Factors in

Table 3: Technological Impediments (in Order of Decreasing Importance)

1. Users forced to adapt to technological shortcomings of VE technology.
2. Lack of cost-effective, high-performance VE technology.
3. Lack of understanding of the important component factors of the VE experience.

Note. VE = virtual environment.

Table 4: Role of National Institutions

1. To provide funding
   - Sponsorship
   - Supply grants
   - Establish consortiums
   - Promote international collaborative research
2. To take an active role to ensure the effective and safe use of VE technology
   - Alert user communities of potential dangers
   - Set up regulatory safety and legal standards for managing aftereffects
3. To define future requirements and concerns
   - Set design standards and guidelines
   - Promote identification of customer needs
   - Identify weaknesses and constraints
   - Promote identification of practical solutions and applications
   - Provide research labs access to updated, online descriptions of application targets
4. To disseminate information
5. To reduce manufacturing costs of VE technology
6. To establish parameters of system specifications

Note. VE = virtual environment.

VE" as a research priority within its Information Technology and Computing Science Funding Initiative, with particular reference to user and interface issues, organizational applications, and disability aids. The U.K. Defense Research Authority has also put joint funding into VE projects under the EPSRC initiative. Projects focusing on the development of effective VE interfaces have also been funded in the United Kingdom and Europe by the European Commission. Across all the European research funding programs, the framework documents have likewise identified VEs as a priority area for applications development and for technology integration, for instance, in education and training and in general manufacturing applications. In this respect the response in the United Kingdom is gathering momentum.

Looking to the future, the respondents' envisioned role of national institutions in realizing the effective use of VE technology is summarized in Table 4. National institutions should serve as sponsors, grant suppliers, and financial supporters and should also establish research programs to initiate research. These institutions should establish consortiums to address high-priority research issues. In particular, a top priority should be the support of fundamental research that will overcome sensory discordances (i.e., identify techniques that create VEs that entail little or no sensory discordances). There is currently a lack of coordination among research efforts, international collaborative research funding and facilitation, and coordination of evaluation and testing across multiple disciplines.

National institutions should assist in setting standards and design guidelines, disseminating the latest research and application findings, and defining future requirements and concerns. They should promote identification of practical solutions (e.g., potential utilization for advanced spaceflight missions) and applications, as well as customer needs. Research laboratories should be provided with access to updated, online descriptions of application targets (e.g., specific medical or military training needs).

Table 5: VE Display Specifications (Not Including Software)[a]

Content

1. Display (provides luminance and optical modulation)
   a. Resolution (horizontal × vertical pixel count)
   b. Format (active display area—pixel-pitch × number of pixels)
   c. Luminance/chrominance (minimum/maximum and uniformity)
   d. Contrast (12 instantaneously perceptible, 2 increment levels: with no ambient)
   e. Gamma (sensor, display matched)
   f. Dynamic range (instantaneous vs. total: includes dimming range)
   g. Gray levels (256 addressable digital levels)
   h. Colors—number and gamut (256 for VGA)
   i. Temporal response (< 16 ms for NTSC video)
2. Optics (couples image to human eye)
   a. See-through vs. occluded (day vs. night operations)
   b. FOV (horizontal × vertical, degrees)
   c. Exit pupil (horizontal × vertical, > 12mm for 40° FOV)
   d. Eye relief (mechanical clearance to cornea vertex, > 25mm)
   e. Modulation transfer function
   f. Distortion (< 5% for 100% overlap, < 1% for partial overlap): geometric distortion correction for flat panels may require real-time, high-resolution image warpers (not currently available cheaply)
   g. Stray light and glare (< 2.5%)
3. Signal or electronics interface (relays data and images to display)
   a. Video format and standards
      i. NTSC (color)/RS-170A (monochrome)
      ii. RS-343 (monochrome 480-, 875-, and 960-line)
      iii. VGA, SVGA, XGA (60 Hz, interlaced, color or monochrome)
   b. Electrical interface (bandwidth vs. number of wires and connector size)
      i. Digital serial or parallel, serial speeds and protocols (e.g., IEEE 488, SCSI, RS 232, 422, 9600 baud, etc.)
      ii. Analog
4. Image source (head mounted, handheld sights or cameras, remote sensors): display format should match sensor format in both geometric and electronic format (horizontal × vertical × bit-depth, and refresh rate or mode)
   Camera
   a. FLIR (RS-170A, RS-343; 8 or 10 bit A/D)
   b. Image intensifier (optically coupled)
   c. CCD & I2CCD camera
   d. Text and data links (GPS, laser range finder, electronic compass, IFF)
   Synthetic
   a. Latency, update and refresh rate
   b. Dynamic range, grey levels, color gamut, bits/pixel
5. Power consumption and safety (based on estimated system duty cycle)
   a. Mission duration
   b. Power source (tethered, untethered)
      i. Vehicle power (type power, max load)
      ii. Battery (type and number required per mission)
   c. Power dissipation, heat generation, temperature requirements
   d. Safety issues, voltages, EMF, heat, weak links, eye protection, etc.
6. Packaging (head or helmet mounting—wearability)
   a. Wt/CG: USAARL Wt/CG performance compatibility, moments of inertia
   b. Helmet constraints
      i. Helmet Wt/CG (subtracts from total allowable head worn Wt/CG)

ii. Suspension stability (web vs. molded liner)
c. Corrective and protective equipment compatibility
i. Eyeglasses
ii. Sun, wind, dust goggles
iii. Nuclear, biological, chemical protective mask
iv. Ballistic, laser protection system
d. Environmental constraints
i. High–low temperature operation and storage
ii. Fungus, salt–fog, dust, humidity, immersion
iii. Shock and vibration (transportation, operation, weapons fire)
iv. EMI (susceptibility, emissions)

Note. VE = virtual environment; VGA = video graphics adaptor; NTSC = National Technical Standard Committee; FOV = field-of-view; XGA = extended graphics adaptor; SCSI = small computer system interface; FLIR = forward looking infrared radar; CCD = charge-coupled device; GPS = global positioning system; EMF = electromotive force; Wt = weight; CG = center of gravity; USAARL = United States Air Force Armstrong Research Laboratory; EMI = electromagnetic interference.
[a]Table provided by S. Ellis.

Governmental agencies should take an active role to ensure the effective and safe use of VE technology. They should be responsible for alerting user communities of potential dangers. They should also take the lead in establishing regulatory guidelines for counteracting harmful aftereffects. Some of the respondents believe, however, that VE technology is not yet ready for standardization or regulation.

In terms of technology, national institutions need to identify strategies to reduce the manufacturing cost of HMD display components. In addition, efforts to standardize descriptions of system parameters are needed to facilitate comparison of studies. An effort to establish initial VE display specifications is presented in Table 5.

4.4. Industrial Impediments

There are three main issues that the respondents suggested are hindering widespread industrial use of VE technology (see Table 6). The first industrial impediment is that the cost effectiveness of VE technology is not well established. Currently, there are poor data links for industrial use, a lack of quality of experience (e.g., malaise and low presence), and a lack of structured, publicly available case study evaluations that specify the added value provided by the use of VE applications over existing systems (Wilson, D'Cruz, Cobb, & Eastgate, 1996). Thus, VE technology does not fare well in the evaluation of cost versus performance and utility versus safety trade-offs. Second, there are the often unrecognized or ignored adverse aftereffects, which will almost certainly lead to products liability lawsuits engendered by incidence and accidents following prolonged VE exposure. Third, usability issues (e.g., visual discomfort and cybersickness) currently make the use of VE systems less than desirable.

5. RESEARCH AGENDA

In addition to responding to the targeted questions summarized earlier, the respondents were also asked to identify in the questionnaire and during the session

Table 6: Industrial Impediments (in Order of Decreasing Importance)

1. Value-added issues
VE technology seems to be too expensive and difficult
Cost–performance and utility–safety trade-offs
Lack of sufficient content that needs VE for communications
Scarcity of structured, publicly available application evaluations
2. Products liability
Ignorance of aftereffects
Lawsuits engendered by incidence and accidents following prolonged VE exposure
3. Usability issues
Visual discomfort and maladaptation
Cybersickness
Issues with navigation and object manipulation
Lack of design guidelines for VE developers that lead to effective performance with limited adverse effects
Cooperation of hardware and software development with knowledge of human adaptation

Note. VE = virtual environment.

collaborations what they considered to be the most important targets for achieving the effective use of VE technology in the short term (next 1–2 years), medium term (within 5 years), and long term (more than 5 years). The questionnaire information and session collaborations were integrated and summarized into the research agenda presented in Table 7. Further input was obtained from the participants subsequent to the special session, in which a ranking of priority research items was conducted. Those research issues directly related to aftereffects and presence are marked as such in Table 7, whereas other research issues are generally related to the need to demonstrate the cost-effectiveness of VE technology. Using Minitab, the ranking data were evaluated using the Kruskal–Wallis *H* test, a nonparametric statistic (Mendenhall & Sincich, 1992). This evaluation indicated that there were significant differences ($H = 85.32$, $p < .0001$) among the research areas ranked. Median responses for the priority (1 = *high* to 5 = *low*) and term data (short, medium, long) were calculated and are presented in Table 7.

During the session, the participants identified the two most critical research issues that need to be resolved. These results were consistent with the results of the rankings in Table 7, in which both issues were ranked of highest importance. These issues are (in order of importance):

1. Establishing the use of standardized subjective and objective measurement of aftereffects—which should be accomplished within 1 year.
2. Identifying and prioritizing the sensory discordances in VEs that lead to aftereffects and their related thresholds (i.e., the level at which these discords lead to sickness and aftereffects)—which should be accomplished within 5 years.

The establishment of countermeasures to aftereffects (such as dual adaptation mechanisms), reducing latencies, and improvements in tracking technology were also ranked as important research issues (see Table 7). During the session the participants suggested that, for the long term, identification of application areas

Table 7: Recommended R & D Agenda to Promote Understanding of Aftereffects and Sense of Presence in VE

Research Area	*Action Item*	*Research Issue*	*Median Priority*	z Value	*Median Term**
Basic knowledge	Determine the various drivers of cybersickness and create a predictive model	A	2	−1.16	M
	Understand sensory discord, human adaptation and readaptation schedules	A	1	−3.19*	M
	Establish countermeasures to aftereffects	A	2	−2.42*	M
	Establish means of determining user susceptibility to cybersickness and aftereffects	A	2	−1.01	S–M
	Establish VE design guidelines	A/P	2	−1.18	M
	Determine the relation between presence, aftereffects, and task performance, considering task specificity	A/P	3	0.93	M
	Identify factors that contribute to VE stimulus strength and determine their relative weightings	A	3	1.21	M
	Establish product acceptance criteria and systems administration protocols	A	3	1.12	M
	Establish a standard operational definition of sense of presence	P	4	2.70*	M
	Establish relative weightings among the controlling variables that drive presence	P	3	2.53*	M
Technology	Create a low-cost HMD that has a wide FOV and is bright, light, and cableless	A/P	2	−1.52	M
	Reduce latencies	A	2	−2.14*	M
	Establish cross-platform software with portability	A/P	3	1.10	M
	Improve tracking technology	A	2	−2.16*	M
	Create haptic devices	A/P	2	−0.19	L
	Create peripheral devices for remaining senses	A/P	3.5	2.17*	L
	Create retinal displays	A	3.5	2.49*	L
	Integrate motion platforms	A/P	2	0.29	M
Evaluation	Make use of standardized subjective and objective measurement of aftereffects	A	1	−3.12*	S
	Make use of standardized subjective and objective measurement of sense of presence	P	2	−0.45	M
Applications	Identify and evaluate value-added VE applications	O	2	−1.60	M
	Develop "killer" applications	O	4	2.10*	M
	Create collaborative VE systems	O	3	1.61	M

Note. $N = 14$ respondents. A = aftereffects; P = presence; O = other; HMD = head-mounted display; FOV = field-of-view; S = short-term (0–1 year); M = medium-term (within 5 years); L = long-term (> 5 years).
*$p < .05$. Factor ranked as significantly more (if negative z value) or less (if positive z value) important than others.

particularly suited to VE technology was of essential importance to the success of this technology. However, the development of "killer" applications was ranked as significantly less important than other research issues in Table 7 ($z = 2.10$, $p < .05$).

The greatest issue of importance, which should be accomplished in the short-term (0–1 year), is standardization and use of measurement techniques for aftereffects. There was general consensus among the respondents on which aftereffects to measure (i.e., vestibular, proprioceptive, and visual), but there is still a need to select standardized measurement approaches for each of these factors.

There was no consensus on how to measure sense of presence. In addition, making use of standardized measures of sense of presence was not ranked significantly ($z = -0.45$, $p < .33$) above other research factors in importance; however, its median priority ranking was relatively high (2; see Table 7). The session participants suggested that, based on the current state of the knowledge, it is unclear whether sense of presence is important for effective human performance in VE systems. Consistent with this supposition, the establishment of a standard operational definition of sense of presence ($z = 2.70$, $p < .05$) and relative weightings among the controlling variables that drive presence ($z = 2.53$, $p < .05$) were both ranked as significantly less important than other research issues in Table 7. Nevertheless, to characterize more fully the sense of presence, factors thought to influence presence were identified by the session participants (see Table 8). Initially the participants

Table 8: Factors Contributing to Sense of Presence

Factor
Object motion lag
Distortions
Temporal
Spatial
Intersensorily
Unimodal
Navigation mode
Feedback
Visual
Auditory
Social
Haptic and tactile
Stereopsis (binocular depth cues)
Human actors
Color gamut
Scene update rate
Spatial frequency
Duration of exposure
Ergonomics of gear
Realism (i.e., visual scene detail)
Vection
Field-of-view
Touch and force feedback
Number of correlated sensory modalities

attempted to rank these factors. On reflection, however, many of the participants found it impossible to rank the importance of a given factor for presence without specifying the VE under consideration. For example, if a task requires a close view of an object and fine hand–eye coordination, then stereopsis is likely to be very important for the sense of presence. However, if the task is one of driving a car along a winding road without going out of the lane, the provision of stereopsis will be irrelevant for presence. This conclusion, however, does not eliminate the need for research on the various factors identified in Table 8. In an effort to provide some guidance, the participants suggested that the factors thought to contribute most to sense of presence include the naturalness of the navigation mode and the veracity of the visual feedback. Visual lag and temporal distortions were thought to have the most deleterious influence on sense of presence, and thus the development of VE systems that minimize these issues should be further pursued.

To address the second most critical issue (i.e., identification of sensory discordances—which should be accomplished in the medium term, within 5 years—factors contributing to aftereffects were identified during the special session (see Table 9). After these factors were identified, a tally was taken in which 12 of the session participants identified up to five factors that they thought were most contributing to aftereffects. In the "importance" tally, the participants indicated whether each of the important factors lead to nausea, disorientation, or oculomotor disturbances and whether their onset is early versus late during VE exposure or after exposure. The indication of which aftereffects dimensions are affected by each factor and when they occur should prove useful in efforts to resolve these issues.

The median importance tally was 7 and the 95% confidence interval for the median was 2.23 to 12.09. Based on this evaluation, visual lag and intersensory distortions (e.g., a disparity between seen and felt limb position) were thought to be of greatest importance to resolving aftereffects. On the other hand, unimodal (i.e., within one sensory system) and temporal distortions were thought to be of less importance than the other factors.

A separate tally was also taken in which the participants indicated the single factor they thought was least important to aftereffects (see Table 9). The median least importance value was 1 and the 95% confidence interval for the median was 0 to 2.77. Based on this evaluation, spatial frequency and scene update rate were thought to be of least importance to resolving aftereffects.

6. SUMMARY AND CONCLUSIONS

The objectives of this article were to identify the relevant research issues in the area of aftereffects and sense of presence in VE technology and to integrate these issues into an R&D agenda entailing specific areas of critical importance for the short, medium, and long term. The research issues identified as being most critical involve (a) standardization and use of aftereffects measurement approaches; and (b) understanding sensory discord, human adaptation, and readaptation schedules that will likely involve the prioritization of factors that drive VE aftereffects.

Table 9: Tally of Factors Contributing to Aftereffects

			Respondents' Tally of Factors Contributing Most to Aftereffects								
			Nausea			*Disorientation*			*Oculomotor*		
Factor	*Least Significant*	*Tally Sum*	*Early During*	*Late During*	*After*	*Early During*	*Late During*	*After*	*Early During*	*Late During*	*After*
Lag											
Object motion	1	3							1	1	1
Visual	2	15[a]	1	1	6	1		2	1	1	2
FOV	1	7	4		1		1	1			
Scene update rate	3[a]	9	1			3		1	1	2	1
Spatial frequency	4[a]	3				1	1	1			
Distortions											
Spatial	0	8				1	1	3			3
Temporal	0	0[b]									
Intersensorial	0	13[a]	3	2	4		1	2			1
Unimodal	1	2[b]						2			
Median	1	7									
95% CI											
Lower CI	0	2.23									
Higher CI	2.77	12.09									

Note. $N = 12$. For the purpose of simplicity, this list divides VE aftereffect into the three subscales of the Simulator Sickness Questionnaire (Kennedy et al., 1993). Other VE aftereffects are likely to exist that are not explicitly listed above, such as postural disequilibrium and sopite syndrome, which were discussed in the text. FOV = field-of-view; VE = virtual environment; CI = confidence interval; Least Significant = Tally of number of respondents voting factor least significant to aftereffects; Tally Sum = The sum of tallies for each factor across the aftereffects dimensions (i.e., nausea, disorientation, and oculomotor).

[a]Above 95% CI for median. [b]Below 95% CI for median.

Without proven reliable and valid measures for aftereffects and presence, no fundamental research can be done. Thus, there will be no way to adequately investigate the wide range of system components and human factors that can affect aftereffects and presence or determine the inherent worth of these constructs. The participants of the special session felt the worth of the sense of presence construct, including its influence on task performance, is still unclear. Ultimately, the value of any VE system (with the possible exception of systems intended solely for entertainment) will be determined primarily by its influence on task performance. Some participants thus suggested that subjective experiences associated with VEs (principally, vection and presence) may be most useful in the design and evaluation of VE systems if it is possible to establish clear, empirically verified predictive relations between these experiences and task performance. Other participants suggested that this relation may be tenuous. The participants agreed that it is of critical and immediate importance to come to understand VE aftereffects well enough to be able to predict their appearance in individuals and to design systems so as to prevent their occurrence in the general population. As the technology develops, and the implementation of VE systems migrates to widely available platforms (e.g., the Internet), understanding the long-term ramifications of aftereffects and presence in terms of ergonomic applications will become ever more important.

This review has concentrated on aftereffects and sense of presence as key to the understanding and use of VEs. The latter is one of the attributes that define the technology, although, as noted, it is a controversial concept and many factors have been suggested as contributing to it. Presence does appear to be intimately related to other attributes—such as interactivity in real time—and seems to be a vital component in the creation of believable (not realistic), coherent worlds. Aftereffects embrace a number of occurrences, including sickness during or after VE participation, disturbance to physiological and other body mechanisms during or afterward, and—perhaps resulting from these types of occurrence—interference with performance within the VE or on other tasks afterward. Although it is undeniable that some people experience some aftereffects within some systems, it is not necessarily the case that VE technology is implicitly harmful. Careful consideration of system components, VE design, and circumstances of use might minimize any potential for harm. As with presence, the components of aftereffects and appropriate methods of measuring them will not be easy issues to address and will require input from a number of disciplines. What will be central to such an effort is the contribution from ergonomics and human factors, addressing the multiplicity of human issues central or related to aftereffects and sense of presence of participation in VEs (see Stanney, Mourant, & Kennedy, in press; Wann & Mon-Williams, 1996; Wilson, 1997). This will best be made through careful, collaborative international research.

VEs are only a tool, and they will do some things better than today's technologies and some things worse. The roles of the research communities will be to establish how to improve the effectiveness and quality of experience of VE participation for participants and user organizations and to establish clear performance benefits for evaluated applications.

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