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Human Factors Issues in Virtual Environments:

A Review of the Literature

Abstract

Virtual environments are envisioned as being systems that will enhance the communication between humans and computers. If virtual systems are to be effective and well received by their users, considerable human-factors research needs to be accomplished. This paper provides an overview of many of these human-factors issues, including human performance efficiency in virtual worlds (which is likely influenced by task characteristics, user characteristics, human sensory and motor physiology, multimodal interaction, and the potential need for new design metaphors); health and safety issues (of which cybersickness and deleterious physiological aftereffects may pose the most concern); and the social impact of the technology. The challenges each of these factors present to the effective design of virtual environments and systematic approaches to the resolution of each of these issues are discussed.

1 Introduction

Efforts to apply virtual reality (VR) technology to advance the fields of medicine, engineering, education, design, training, and entertainment are currently underway. The medical profession has expressed its desire to use VR systems as training tools (Stytz, Frieder, & Frieder, 1991); human-factors specialists are using VR for user-system analysis and design (Scott, 1991); scientists are utilizing VR to visualize complex data (Defanti & Brown, 1991); stock market analysts want to use VR to predict market trends and achieve financial gains (Coull & Rotham, 1993); and the military currently uses VR to carry out virtual war scenarios and training exercises (Dix, Finlay, Abowd, & Beale, 1993). Interest in this technology is so widespread that the U.S. government asked the National Research Council to identify and determine U.S. VR research priorities (Adam, 1993; Durlach & Mavor, 1995).

The reality is, however, that a considerable amount of systematic research must be carried out in order for VR to fulfill its potential. Researchers need to focus significant efforts on addressing a number of human factors issues if VR systems are to be effective and well received by their users. Perhaps this need was best articulated by Shneiderman (1992) who stated that "analyses of VR user-interface issues may be too sober a process for those who are enjoying their silicon trips, but it may aid in choosing the appropriate applications and

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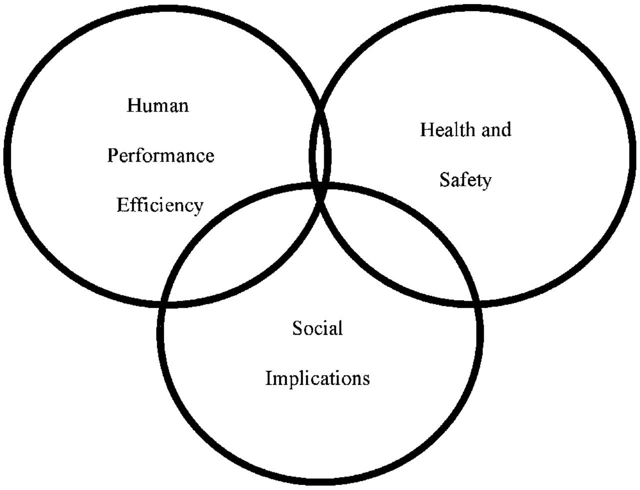

Figure 1. *Areas of human-factors research for virtual environments.*

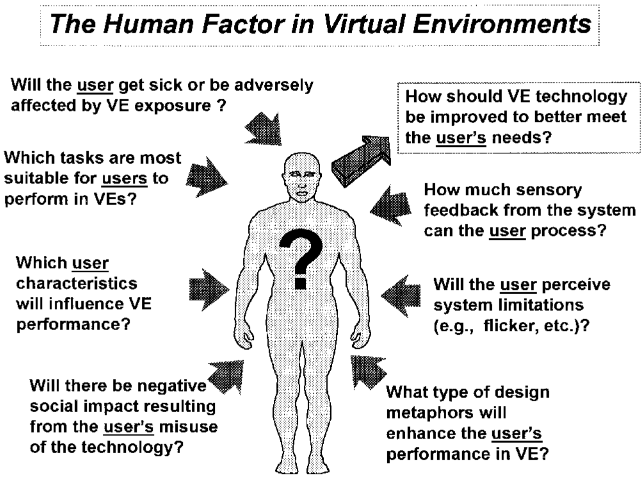

Figure 2. *The human factor in virtual environments.*

refining the technologies" (p. 224). We believe human-factors practitioners can assist in making significant contributions to the theoretical understanding of human-virtual environment interaction (HVEI). This paper has organized the area of human factors research in virtual environments (VEs) into three primary subtopics: human performance efficiency in virtual worlds; health and safety issues; and potential social implications of VE technology. (See Figure 1.) Some of these topics have been looked at rather briefly in the past (Thomas & Stuart, 1992). The objective of the present paper is to provide a comprehensive overview of each of these human factors research areas and to provide insight into approaches for their systematic resolution.

Designing usable and effective interactive virtual worlds is a new challenge for system developers and human-factors specialists. Due to the close bond between the user and the system within VEs, it may be impossible to follow past traditions and segregate human factors from design issues when striving to achieve the potential of VE technology. It is the capabilities and limitations of the user that many times will determine the effectiveness of virtual worlds. (See Figure 2.) An understanding of human-factors issues can thus be used to provide a systematic basis by which to direct future VE research efforts aimed at advancing the technology to better meet the needs of its users. In the following sections, three primary areas of human-factors research in VEs will be addressed, and issues requiring further research will be identified.

2 Human Performance Efficiency in Virtual Worlds

Computer speed and functionality, image processing, synthetic sound, and tracking mechanisms have been joined together to provide realistic virtual worlds. A fundamental advance still required for VEs to be effective is to determine how to maximize the efficiency of human task performance in virtual worlds. In many cases, the task will be to obtain and understand information portrayed in the virtual environment. As Wann and Mon-Williams (1996, p. 845) stated, in such cases "the goal is to build (virtual) environments that minimize the learning required to operate within them, but maximize the information yield." Maximizing the efficiency of the information conveyed in VEs will require developing a set of guiding design principles that enable intuitive and efficient interaction so that users can readily access and comprehend data. The design approach used for more traditional simulation systems (e.g., teleoperated systems) was generally "trial and error" due to the paucity of general, non-system-specific design guidelines (Burdea & Coiffet, 1994). If VE tasks are designed in such an ad hoc manner, however, the potential benefits of the

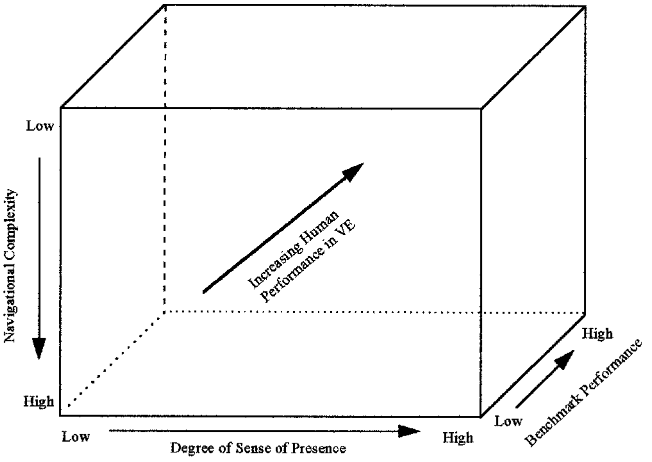

Figure 3. *Components of human performance in virtual environments.*

virtual world, such as enhanced understanding and transfer of training, may be compromised. While it is difficult to gauge the importance of the various human-factors issues requiring attention, it is clear that if humans cannot perform efficiently in virtual environments, thereby compromising the effectiveness of the HVEI or the transfer of training, then further pursuit of this technology may be fruitless.

In order to determine the effectiveness of a VE, a means of assessing human performance efficiency in virtual worlds is first required. This is easier said than done. In contrast to past HCI studies, VE performance measures need to focus on more than task outcome to be effective. Due to the complex nature of HVEI, it may be essential to develop effective multicriteria measures to evaluate human performance in virtual environments. Factors contributing to human performance in VEs predictably include the navigational complexity of the VE, the degree of presence provided by the virtual world, and the users' performance on benchmark tests. (See Figure 3.)

If individuals cannot effectively navigate in VEs, then their ability to perform required tasks will be severely limited. Wann and Mon-Williams (1996) have discussed the edge and object information, as well as the dynamic global changes in features and textures that are necessary to achieve effective navigational performance. Beyond determining such design principles that specify the necessary cues to support navigation, a designer must determine how a user should move about a virtual world. While some developers have incorporated "various permutations of windowing to allow people to move" about VEs (Laurel, 1994), newer designs such as portals, spirals, sliders, and tow planes hold promise for enhanced VE interaction. Nilan (1992) has explored the mapping of a user's cognitive space to the design of the VE to enhance navigational performance. Darken and Sibert (1996) have developed mediators and modalities to assist with VE navigation. These approaches are likely to achieve varying degrees of success prior to focusing on standard(s) for VE navigation.

Due to the current issue of users becoming lost in considerably less-complex, hierarchical computer environments (Sellen & Nicol, 1990), the design and development of standardized navigational techniques that assist individuals in maintaining spatial orientation within VEs may prove to be one of the most important issues to resolve in VE design (Darken & Sibert, 1996). Without adequate means of moving about VEs, developers cannot expect to maximize human performance. One potential approach to addressing this issue is to develop a means of measuring the "navigational complexity" of a VE (i.e., how challenging it is to move from point A to point B). Such a measure would likely be dependent on the sensorial cues and spatial mediators (e.g., maps) provided by an environment, as well as on the spatial ability of the navigator. Navigational complexity likely varies between VE designs and even within a given VE, thus potentially becoming a diagnostic tool for evaluating the effectiveness of a given VE design (e.g., redesign could be directed to areas with high navigational complexity). Mental maps (Siegel, 1981), wayfinding (Vishton & Cutting, 1995), dead reckoning (Gallistel, 1990), homing (Adler, 1971), spatial orientation (Adolfson & Berghage, 1974; Thorndyke & Statz, 1980), time to collision (Lee, 1976), geographical orientation (Clark & Malone, 1952), and vestibular functions (Howard, 1984) are a few of the fields with technical knowledge regarding the perceptual issues involved with navigation in virtual environments. Most researchers of these above areas have not yet adapted their knowledge to virtual environments. When they do, the field of perception is likely to explode because VEs, which can be manipulated to present an infinite number of perceptual experiences, offer an experimental paradigm to study perception that is far superior to the prism spectacle of 100 years ago. These environments may provide the necessary tools to assist researchers in disclosing the mysteries of human perception (Findlay & Newell, 1995). For example, a simulated visual, auditory or haptic stimulus could be manipulated to determine the relative importance of different types of cues.

The degree of presence experienced by an individual may influence human performance (Fontaine, 1992; Zeltzer, 1992). Presence is a factor of both the vividness of an experience and the level of interaction (Sheridan, 1992; Steuer, 1992). It is commonly considered that operation of a VE system that provides a high degree of presence is likely to be better accomplished than one where such perceptions are not present. Little or no systematic research is available, however, to substantiate this assumption. This may be due to the lack of systematic methods for evaluating and defining the presence requirements for different applications. It is also likely that this lack of information is related to the inadequate manner in which human performance is measured (Lane, 1986). At present, presence is generally evaluated via either questionnaires (Hendrix & Barfield, 1995; Singer, Witmer, & Bailey, 1994) or through as yet non-validated analytical models (Slater & Usoh, 1993). A desirable goal would be to develop operational models of presence with objective measures that could assist in determining the appropriate level of vividness/fidelity and interaction required for a given set of task characteristics. It will also be necessary to have solid measures of human performance in order to show that more presence leads to better performance.

The ability of an individual to effectively complete a set of VE benchmark tests may also influence performance (Burdea et al., 1994). These tasks would include, but are not limited to, the ability to move about the virtual world (i.e., move forward, and backward, move up, and down, turn, etc.), manipulate or track virtual objects, locate virtual sounds, respond to kinesthetic force feedback, or perform visual tasks (i.e., perceive and discriminate colors; judge virtual distance; search for, recognize, and estimate the size of virtual objects). Recently, Lampton, Knerr, Goldberg, Bliss, Moshell, and Blau (1994) have developed the Virtual Environment Performance Battery (VEPAB). The VEPAB includes the determination of visual acuity, locomotion ability, object manipulation ability, tracking ability, and reaction time while viewing virtual worlds. The VEPAB is a move toward benchmarking VE performance. This battery needs to incorporate higher-level skills (e.g., a user's navigational ability), as well as multisensory benchmarks for the auditory and kinesthetic senses to provide a more-comprehensive assessment of HVEI performance. The results from such tests could provide a baseline from which to judge the effectiveness of a VE. For example, if the evaluation of a VE led to low baseline data, one would not expect high user task performance from such an environment. In such cases, users' task performance would be limited by their inability to function operationally in the virtual world.

Once a comprehensive set of factors influencing human performance in VEs has been established, more definitive studies of HVEI can be conducted. Human performance in VEs will likely be influenced by several factors, including task characteristics, user characteristics, design constraints imposed by human sensory and motor physiology, integration issues with multimodal interaction, and the potential need for new visual, auditory and haptic design metaphors uniquely suited to virtual environments. In order to maximize human performance in VEs, each of these factors must be considered.

2.1 Task Characteristics

One important aspect that will directly influence how effectively humans can function in virtual worlds is the nature of the tasks being performed. Some tasks may be uniquely suited to virtual representation, while others may not be effectively performed in such environments.

To justify the use of VE technology for a given task, when compared to alternative approaches, the use of a VE should improve task performance when transferred to the real-world task because the VE system capitalizes on a fundamental and distinctively human sensory, perceptual, information-processing, or cognitive capability.

It is important to determine the types of tasks for which these types of benefits can be obtained by using VE technology. Wann and Mon-Williams (1996) have suggested that data and feature analyses (e.g., dimensional assessment, visual detail enlargement, design envisioning, contingency evaluation) and data visualization are viable tasks for gleaning such benefits. Viable tasks can be systematically specified by obtaining an understanding of the relationship between task characteristics and the corresponding VE characteristics (i.e., stereoscopic 3-D visualization, real-time interactivity, immersion, multisensory feedback) that effectively support their performance both within the VE and upon transfer to the real-world task.

Some evidence of the benefits of stereoscopic visualization comes from work by Kim, Tendick, and Stark (1993). In investigating the benefits of stereo cues in a virtual pick-and-place task, they found that a stereoscopic display was far superior to a monoscopic display. Interestingly, however, performance with the monoscopic display was just as effective as the stereoscopic display when visual perspective display enhancements were provided (i.e., ground grids and projection lines). Similar benefits from stereo were demonstrated by Wickens, Merwin, and Lin (1994). Pepper, Smith, and Cole (1981) have also found that stereoscopic display performance is generally superior to monoscopic performance; however, they found the extent of improvement was dependent on the task, visibility, and learning factors. Kim et al (1993) suggest that, for simple telemanipulation tasks, monocular depth cues and cognitive cues (accumulated through learning and past experiences) may be sufficient for effective performance. They argue that when tasks become more complex, and the monocular and cognitive cues provided are insufficient or lacking, stereoscopic cues will enhance performance. These suggestions may explain why Kozak, Hancock, Arthur, and Chrysler (1993) found no significant transfer-of-training benefits from virtual reality training, as compared to real-world and no training conditions, on a pick-and-place task. The task used in this experiment, picking up a can and placing it in a target location, was one which subjects would have had many cognitive cues from past experience (e.g., from picking up soda cans or drinking glasses). Therefore, the additional stereoscopic cues provided during the VR training trials may not have significantly added to the learners' performance on the task.

Evidence of transfer from VR training of navigational tasks (i.e., building navigation) has been found by Regian and Shebilske (1992). Based on the results of Kim et al. (1993), it may be suggested that the navigational tasks used in this study may have been more complex or less familiar than the pick-and-place tasks used by Kozak et al. (1993), thus leading to performance benefits provided by the additional stereoscopic cues. Additional study is needed to determine how to enhance transfer of training via VE training; this will be predictably antedated by the determination and selection of appropriate tasks to train.

While the benefits of interactivity and immersion to both performance and presence are often cited (Burdea et al., 1994; Kalawsky, 1993; Steuer, 1992), little direct empirical evidence exists. Proffitt and Kaiser (1995) performed an experiment that demonstrated the benefits of interactivity. In this experiment, subjects standing in front of a hill judged its incline under three conditions: verbal; visual (using a hand-held modified compass to approximate the angle); and haptic (placing their hands on a board and moving the board until its position approximated the angle). Through the interactivity of the haptic condition, subjects were able to "feel" the angle, which resulted in significantly better performance than the other conditions. Benefits of interactive displays in medicine, such as the ability to interactively explore complex spatial and temporal anatomical relationships, have also been cited (McConathy & Doyle, 1993; Meyer & Delaney, 1995; Wright, Rolland, & Kancherla, 1995). In fitness performance, highly interactive exercise environments have been shown to produce significantly more mechanical output (i.e., greater RPM, total calories burned, and calories burned per minute) and promote greater and more consistent participation than less interactive environments (Cherry, 1995).

While these early studies provide evidence for the benefits of interactivity, future research will need to address the types and levels of interactivity that are best suited to given task profiles. For example, Williams, Wickens, and Hutchinson (1994) found that interactivity had a differential effect that was dependent on task workload. In this study, interactivity enhanced human performance on a navigational training task under normal workload conditions. When the workload was increased and mental rotation demands were recruited to orient a fixed north-up map, however, individuals trained in the interactive condition performed less effectively than those who studied a map. This suggests that interactivity is beneficial to the extent that it is maintained within human information-processing limitations (Card, Moran, & Newell, 1983). Thus, the benefits of interactivity should not be universally assumed. Designers should recognize that interactivity brings with it increased workload demands that could negate its ability to enhance human performance.

The benefits of immersion have even less empirical support than interactivity. Esposito (1995) attempted to empirically verify the benefits of immersion using a puzzle construction task; however, no definitive conclusions about immersion could be drawn. Although there is limited direct empirical evidence to support the benefits of immersion, considerable indirect evidence exists. Greeno, Smith, and Moore (1993), for example, suggest that knowledge of how to perform a task is embedded in the contextual environment in which the task is to be performed and is not an independent property available for any situation. Druckman and Bjork (1994) further suggest that only when a task is learned in its intended performance situations can the learned skills be used in those situations. Thus, learners are thought to use environmental contextual cues to support and mediate their task actions. Further, transfer of training theories suggest that positive transfer increases with the level of original learning as long as structurally similar stimuli and responses are available and required for both the training and transfer tasks (Schmidt & Young, 1987). The implication is that, if virtual environments immerse learners in environments similar to the intended task environments, it follows that VE training should promote more original learning and greater positive transfer. Further study is indicated to empirically verify the benefits of immersion in virtual environments. One issue is how to isolate the benefits of immersion; to immerse individuals in a VE exposes them to 3-D stereoscopic views and interactivity with virtual objects. Thus, the benefits of stereo and interactivity must be factored out before the benefits of immersion can be determined. To add to this difficulty, it is well known that more practice leads to improved learning. Thus, when studying factors such as immersion, how does one equilibrate training time in the experimental (VE) and control system? Is run time, per se, the controlling factor? Or is it number of training trials? If these are not possible, how else can experimental factors be controlled to minimize confounding effects? This is an age-old problem in behavioral science, but it should not be overlooked when comparing human performance using different technologies. It is essential to control for such factors so that it is not erroneously concluded that human performance is enhanced by immersion (or other factors) when the improved VR performance is directly related to the fact that subjects received more training time or training trials.

2.2 User Characteristics

An important aspect influencing human VE performance is the effect of user differences. These differences, to provide a simplified analysis, can be with the input (e.g., interpupilliary distance), throughput (e.g., cognitive or perceptual styles), or output (i.e., human performance). Significant individual performance differences have already been noted in early VE studies (Lampton et al., 1994). User characteristics that significantly influence VR experiences need to be identified in order to design VE systems that accommodate these unique needs of users. User differences have already been reported to influence the sense of presence (Barfield & Weghorst, 1993) and cybersickness experienced by VE subjects (Parker & Harm, 1992). What is not as obvious are which user characteristics have a subtle impact and which substantially alter virtual experiences.

In order to determine which user characteristics may be influential in VEs, one can examine studies in human-computer interaction (HCI). While both HCI and HVEI involve human-computer interaction, due to differences between them (i.e., HCI is generally from an exocentric frame of reference, while HVEI is generally from an egocentric perspective), earlier HCI studies may not directly apply to HVEI but can provide potential insights. A significant amount of research has focused on understanding the influences of user characteristics in HCI. (For a summary of a number of notable studies, see Egan, 1988.) Even though important, this research has yet to provide firm evidence as to which aptitudes are the most influential in HCI. The absence of definitive user models and theories makes challenging the process of identifying user characteristics significant to VE interaction. Yet, while it is easy to say that these "impedance matches" may be task specific, we believe that there are sufficient generalizations possible such that dependence on the "task specific" excuse should be avoided at all costs, since this comment is so non-informative.

In HCI one of the primary user characteristics that interface designers adapt to is the level of experience, or the expert-versus-novice paradigm (Dix et al., 1993; Eberts, 1994; Egan, 1988). Eberts (1994) noted that experts and novices have diverse capabilities and requirements that may not be compatible. Thus, computer systems need to be adaptable to these diverse needs. Experience level influences the skills of the user, the abilities that predict performance, and the manner in which users understand and organize task information. In examining the influences of experience on HVEI, one could predict that experience would influence the skill with which users interact with the VE and the manner in which users mentally represent a virtual environment over time. Such differences could affect the perceived navigational complexity of a VE and the benchmark performance of users.

Another adaptive approach is to capitalize on the plasticity of human cognitive abilities. Several HCI studies (Egan & Gomez, 1985; Gomez, Egan, & Bowers, 1986; Vicente, Hayes, & Williges, 1987; Stanney & Salvendy, 1995) have suggested that, in general, technical aptitudes (e.g., spatial visualization, orientation, spatial memory, spatial scanning) are significant in predicting HCI performance. These studies generally focused on information search tasks, which predictably share characteristics with many VE tasks that involve navigation (e.g., architectural walk-throughs or training grounds, such as battlefields, which users must search through) or when VEs are used to organize and structure information databases. The HCI studies indicated that individuals who score low on spatial memory tests generally have longer mean execution times and more first-try errors. These studies also suggest that the difficulties experienced by low-spatial individuals were particularly related to system navigation issues—users often report being "lost" within hierarchical menu systems (Sellen et al., 1990). These findings are particularly relevant to VEs that often place a high demand on navigation skills. In fact, VE users are already known to become lost in virtual worlds. McGovern (1993) found that operators of teleoperated land vehicles, even when using maps and landmarks, have a propensity for becoming lost. This result is not surprising since knowledge acquisition from maps is more challenging for some individuals than for others and has been found to be associated with high visual/spatial ability (Thorndyke & Statz, 1980).

The issue is thus how to assist low-spatial users with maintaining spatial orientation within virtual worlds. Some insight into this issue was provided by a study that indicated that, although low-spatial individuals are unable to mentally induce the structure of multidimensional complex systems, they are capable of recognizing the structure of systems when they are well organized and when focus is placed on acquiring their structure (Stanney & Salvendy, 1994). Initial interactions with VEs by low-spatial individuals may thus be best focused on system structure (i.e., layout) exploration rather than task accomplishments, until users have recognized the spatial structure of the virtual world. (Note: A prerequisite to this suggested approach would be for the VE to be well organized using a salient structure). If task workload is high during the initial stages of system use, it is likely that low-spatial individuals will have limited ability to generate an accurate representation of the VE layout (Williams et al., 1994).

Predictably, anyone who has performed human subjects research with VEs will have noted the marked diversity in users' abilities to move about and manipulate objects in a virtual world. While some users experience no difficulties with these tasks, others find them non-intuitive and challenging to accomplish. It should be noted that these early HVEI findings are referring to largely visual virtual worlds. The problem may compound as we place greater emphasis on audio, kinesthetic, and haptic interaction modes in virtual environments. Thus, while motor ability has not been found to consistently predict human computer performance (Egan, 1988), it may become more influential during HVEI. It is therefore essential that human-factors analysis be devoted to understanding the influences of various aptitudes, such as motor and verbal abilities, on HVEI.

Another user characteristic that may influence HVEI is personality. Personality traits have generally not been found to significantly predict computer performance (Egan, 1988), possibly because of the low retest reliabilities of most personality tests (Peterson, Lane, & Kennedy, 1965). Nonetheless, personality traits may become increasingly important during more-complex interactions such as those experienced in virtual environments. Particularly if HVEI is modeled after human-human communication (Eberts, 1994) or human-environment interaction, the influences of personality may become more influential. Methods for improved measurement should be developed to facilitate the investigation of these effects.

Age is another factor that could affect HVEI. Age is influential in determining how much difficulty a user will experience in learning a system (Egan, 1988). The more complex a system becomes, the more influential are the effects of age, particularly if information from different sensory channels is to be integrated. This is disturbing since it is predictable, with their multimodal interaction and complex visual scenes, that VEs will oftentimes be more complex than the systems used in past HCI studies. With significant age effects it would thus be beneficial to determine how to adapt VEs to the needs of older individuals. The manner in which age influences computer performance, however, has yet to be fully understood.

Deficits in perception and cognition, which are often experienced by the elderly (Birren & Livingston, 1985; Fisk & Rogers, 1991; Hertzog, 1989; Salthouse, 1992), may lead to a reduction in the information perceived from VE scenes. For example, diminution of sensory input from the eyes experienced by older individuals (Rosenbloom & Morgan, 1986) may impede visual perception. More specifically, older individuals generally experience lower visual acuity and reduced contrast sensitivity that could limit sensory input from a virtual environment. This reduction in perception could, in turn, present difficulties to elderly users when navigating virtual worlds or manipulating virtual objects. It is important to consider the influences of age on HVEI, particularly due to the potential this technology has for providing the elderly, who are often isolated from the world, with stimulating interactive activities.

There are thus several user characteristics that may be relevant to HVEI. These factors need to be identified and the level of their influence on HVEI needs to be determined.

2.3 VE Design Constraints Related to Human Sensory Limitations

In order for designers to be able to maximize human efficiency in VEs, it is essential to obtain an understanding of design constraints imposed by human sensory and motor physiology. Without a foundation of knowledge in these areas, there is a chance that VE systems will not be compatible with their users. VE design requirements and constraints should thus be developed by taking into consideration the abilities and limitations of human sensory and motor physiology. The physiological and perceptual issues that directly impact the design of VEs include visual perception, auditory perception, and haptic and kinesthetic perception. Each of these issues is discussed below.

2.3.1 Visual perception. The design of visual presentations for VEs is complicated because the human visual system is very sensitive to any anomalies in perceived imagery (Larijani, 1994). The smallest, almost imperceptible anomaly becomes dreadfully apparent when motion is introduced into a virtual scene, because visual flow field cues take on an unnatural appearance (Kalawsky, 1993). More specifically, if a VE is unable to generate approximate optical flow patterns, then the user becomes very aware that the experience is not natural.

For example, in VEs used for driver training, observers may perceive moving objects during self-motion (e.g., other traffic while driving). Berthelon and Mestre (1993) have explained drivers' perception of moving vehicles in terms of Gibson's (1979) optical flow theory. The implication is that for more-effective visual displays, optical flow needs to be taken into account when designing VE driving simulators, as is now being done by Levine and Mourant (1994).

Overall, the presentation of motion scenes in VEs needs further study in order to ensure that the most-effective visual scenes are developed. Presently VE systems ordinarily provide the same image to both eyes and thus do not present a "real" stereo image. When they do provide stereo, adjustments for the interpupillary distance (IPD) are critical, and these adjustments can cause problems during post-exposure readaptation to normative conditions. Also, VE systems almost always do not render binocular movement parallax properties and will not in the future unless they are tied to accommodation.

Another major factor is the viewer's visual field when wearing a head-mounted display (HMD). There are many different ways to graphically present the field of view (FOV) of an individual, including polar charts, equal-area projection plots, and rectilinear plots (Kalawsky, 1993). These multiple approaches make it difficult when comparing VE systems based on their FOV. Further, manufacturers' estimates of FOV are often inaccurate (Rinalducci, Mapes, Cinq-Mars, & Higgins, 1996; Robinett & Rolland, 1992). Thus, researchers must often independently determine the FOV of their device through engineering or optical analyses. Rinalducci et al (1996) have recently developed a simple psychophysical procedure for determining the FOV for an HMD which involves matching the size of an HMD image to that of an afterimage having a known angular subtense. With any of these methods, it is important to overlay the graphical dimensions of the observer's visual field onto obscuration plots. HMDs substantially reduce the FOV of a user, obscuring the perception of motion in the peripheral vision. Current systems are generally limited to a FOV of 70° per eye and do not provide enough peripheral vision. Many VE tasks may require FOVs of 100° or more in order to achieve a feeling of immersion. As the FOV is expanded, however, the resolution of the projected images declines (Biocca, 1992a). In addition, wider FOVs have been implicated in greater sensations of motion sickness (Pausch, Crea, & Conway, 1992). It is thus essential to determine what FOV is required to perform different kinds of VE tasks effectively. Then the extent to which FOVs need to be enlarged can be specified. Arthur (1996) is investigating the effects of FOV on human task performance using a representative set of spatial tasks. The results from this study are intended to provide design guidelines to HMD and VE developers so that an appropriate FOV can be chosen for a given application and task.

Another physiological issue in VEs is related to stereopsis. Stereopsis describes the perceptual transformation of differences between the two monocular images seen by the eyes. It is a functional component of depth perception, though, and not an essential element for perception of depth. Stereopsis is important to study because of the emphasis placed on the benefits of depth perception to virtual world performance (Ellis & Bucher, 1994; Ellis & Menges, 1995; McDowall, 1994). Modern VE systems present problems directly related to the lack of appropriate stereopsis (Mon-Williams, Wann, & Rushton, 1993; Rushton, Mon-Williams, & Wann, 1994).

The portion of the visual field shared by both eyes is known as the binocular field of vision (i.e., stereopsis) (Haber & Hershenson, 1973). Partial binocular overlap can be used in VEs to achieve depth perception, in which a monocular image is displaced inwards or outwards. Such partial overlap can be used to realize wide FOVs with smaller and lighter HMDs. In order to have effective depth perception in VEs with partial overlap, however, the required degree of overlap must be determined. Currently, the amount of overlap required is not well understood. Human-factors practitioners need to perform perceptual and human performance studies to determine if partial overlap is acceptable and what levels are required for different applications. (See Mon-Williams et al., 1993; Rushton et al., 1994.)

Another issue related to stereopsis is binocular rivalry (Kalawsky, 1993). When two different images are presented to an observer, the image of the dominant eye often dominates the visual system. Binocular rivalry effects, which can be extremely disturbing sensations, occur when the dominant image alternates from one eye to the other. Differences in size, display scene representation and complexity, brightness, and hue can all lead to binocular rivalry effects. Such effects are common in synthetic scenes such as VEs. Rivalry is especially present in augmented (overlaid) reality systems. A means of moderating or eliminating these disturbing effects is needed for VEs to receive wide user acceptance.

For VE designers trying to achieve stereo depth perception it is important to note that lateral image disparity (in the range of 0° to 10°) leads to depth perception (Kalawsky, 1993). On the other hand, vertical image disparities do not convey any depth cues. In fact, small amounts can lead to double vision (diplopia). Although users can adapt to diplopia in 15 to 20 minutes, they must readjust to visual scenes when they reenter the real world. Such distortion could lead to safety issues. Debriefing protocols that instruct users how to proceed after VE interaction may be needed to assure the safety of users.

It is also important to note that depth perception is dependent on whether a scene is static or dynamic (Russell & Miles, 1993). Depth perception of dynamic scenes, such as those in VEs, is very complex and not well understood. It is thus important to perform depth-perception studies with both static and dynamic scenes, since the results from the former may not generalize to the later.

2.3.2 Auditory perception. In order to synthesize a realistic auditory environment, it is important to obtain a better understanding of how the ears receive sound, particularly focusing on 3-D audio localization. Audio localization assists listeners in distinguishing separate sound sources. Localization is primarily determined by intensity differences and temporal or phase differences between signals at the ears (Begault & Wenzel, 1993; Middlebrooks & Green, 1991). More specifically, the degree to which one sound masks another depends on the relative frequency, intensity, and location of sound sources. Audio localization is affected by the presence of other sounds and the direction from which these sounds originate. The human ear can locate a sound source even in the presence of strong conflicting echoes by rejecting the unwanted sounds. Biocca (1992a) states that “the aural realism of virtual spaces requires replicating the spatial characteristics of sounds like the changing intensity of a race car engine as . . . it screeches past.” The human ear can also isolate a particular sound source from among a collection of others all originating from different locations (Koenig, 1950). In order to effectively develop aural displays, this ability of listeners to track and focus in on a particular auditory source (i.e., the cocktail party effect) needs to be better understood.

Auditory localization is understood in the horizontal plane (left to right). Sounds can arrive 700 microseconds earlier to one ear than the other and the sound in the farther ear can be attenuated by as much as 35 decibels relative to the nearer ear (Middlebrooks et al., 1991). For example, if a listener perceives a sound coming from the right, generally the sound has arrived to the right ear first and/or is louder in the right ear as compared to the left. When sound sources are beyond one meter from the head, these interaural time and intensity differences become less pronounced in assisting audio localization.

Vertical localization in the median plane cannot depend on interaural differences (i.e., as long as the head and ear are symmetrical). When a sound is directly in front of (or behind) a listener, the interaural differences are zero; however, the listener is still somehow able to localize the sound. In such cases, the anatomy of the external ear (i.e., the pinna) is thought to produce changes in the spectrum of a sound (i.e., spectral shape cues) that assist in localizing the sound (Fisher & Freedman, 1968; Middlebrooks et al., 1991).

Thus, in order to effectively characterize 3-D audio localization, binaural localization cues received by the ears can be represented by the pinna cues, as well as by interaural acoustical differences. Recently, a Head Related Transfer Function (HRTF) has been used to represent the manner in which sound sources change as a listener moves his/her head and can be specified with knowledge of the source position and the position and orientation of the head (Butler, 1987; Cohen, 1992). The HRTF is dependent on the physiological makeup of the listener’s ear (i.e., the pinna does a nonlinear fitting job in the HRTF). Recent advances have allowed for the development of personalized HRTFs (Crystal Rivers Engineering, 1995). These personalized functions still require a significant amount of calibration time. Ideally, a more-generalized HRTF could be developed that would be applicable to a multitude of users. This may be possible since the transfer functions of the external ear have been found to be similar across different individuals, although there tends to be a downward shift in spectra frequency with increasing physical size (Middlebrooks, Makous, & Green, 1989).

2.3.3 Physiology of haptic and kinesthetic perception. A haptic sensation (i.e., touch) is a mechanical contact with the skin. It is important to incorporate haptic feedback in VEs because such feedback has been found to substantially enhance performance (Burdea et al., 1994). For example, by incorporating haptic feedback into synthetic molecular modeling systems, the problem-solving ability of chemists was significantly enhanced (Brooks, Ouh-Young, Batter, & Kilpatrick, 1990; Minsky, Ouh-Young, Steele, Brooks, & Behensky, 1990).

Three mechanical stimuli produce the sensation of touch: a displacement of the skin over an extended period of time, a transitory (a few milliseconds) displacement of the skin, and a transitory displacement of the skin that is repeated at a constant or variable frequency (Geldard, 1972). Even with the understanding of these global mechanisms, however, the attributes of the skin are difficult to characterize in a quantitative fashion. This is due to the fact that the skin has variable thresholds for touch (vibrotactile thresholds) and can perform complex spatial and temporal summations that are all a function of the type and position of the mechanical stimuli (Hill, 1967). So as the stimulus changes so does the sensation of touch, thus creating a challenge for those attempting to model synthetic haptic feedback.

Another haptic issue is that the sensations of the skin adapt with exposure to a stimuli. More specifically, the effect of a sensation decreases in sensitivity to a continued stimulus, may disappear completely even though the stimulus is still present, and varies by receptor type. Phasic receptors are ones that rapidly adapt and relate to pressure, touch, and smell. Tonic receptors, which are related to pain and body position, slowly adapt and may have an afterimage that persists even once the stimulus is removed.

Surface characteristics of the stimulus also influence the sensation of touch. For a hard surface to be felt after initial contact, active pressure must be maintained. The sensation of textured surfaces requires some relative motion between the surface and the skin to be maintained. Soft surfaces can exert and maintain a slight positive reaction against the skin after the initial contact without active pressure or relative motion. Most current systems provide limited haptic feedback, generally isolated to the hand. For example, electrotactile and vibrotactile devices have been developed to simulate the sensation of texture and other surface illusions on the hand (Kaczmarek, Webster, Bach-y-Rita, & Thompkins, 1991). More fully haptic feedback may be needed to enhance performance and presence (Biocca, 1992a). Current exoskeletons are cumbersome and expensive. A less-invasive means of providing full haptic feedback is desirable.

In order to communicate the sensation of synthetic remote touch, it is thus essential to have an understanding of the mechanical stimuli which produce the sensation of touch, the vibrotactile thresholds, the effect of a sensation, the dynamic range of the touch receptors, and the adaptation of these receptors to certain types of stimuli. The human haptic system thus needs to be more fully characterized, potentially through a computational model of the physical properties of the skin, in order to generate synthesized haptic responses.

Kinesthesia is an awareness of the movements and relative position of body parts and is determined by the rate and direction of movement of the limbs; the static position of the limbs when movement is absent; tension signals originating from sensory receptors in the joints, skin, and muscles; and visual cues (Kalawsky, 1993). Kinesthetic issues for VE design include the facts that a small rate of movement of a joint can be too small for perception, that certain kinesthetic effects are not well understood (e.g., tensing the muscles improves movement sense), and that humans possess an internal mental image of the positions of limbs/joints that is not dependent on actual sensing information. There is thus a great deal to be learned about how to integrate the capacities of the human into the design of a VE.

2.4 Integration Issues with Multimodal Interaction

While developers are focusing on synthesizing effective visual, auditory, and haptic representations in virtual worlds, it is also important to determine how to effectively integrate this multimodal interaction. One of the aspects that makes VEs unique from other interactive technologies is their ability to present the user with multiple inputs and outputs. This multimodal interaction may be a primary factor that leads to enhanced human performance for certain tasks presented in virtual worlds. Early studies have already indicated that sensorial redundancy, such as visual, auditory, and tactical feedback (Fukui & Shimojo, 1992), can enhance human performance in virtual worlds. One demonstration of the benefits of such multimodal user feedback was provided by Massimino and Sheridan (1994) who found enhanced performance with visual and force feedback, as compared to no force feedback, in a peg-in-hole task. There is currently, however, a limited understanding on how to effectively provide such sensorial parallelism (Burdea et al., 1994). When sensorial redundancy is provided to users it is essential to consider the design of the integration of these multiple sources of feedback. One means of addressing this integration issue is to consider the coordination between sensing and user command, and the transposition of senses in the feedback loop.

Command coordination considers the user input as primarily monomodal (e.g., through gesture or voice) and feedback to the user as multimodal (i.e., any combination of auditory, visual, and/or haptic). There is limited understanding on such issues as

(1) Is there any need for redundant user input (e.g., voice and direct manipulation used to activate the same action)?
(2) Can users effectively handle parallel input (e.g., select an object with a dataglove at the same time as directing a search via voice input)?
(3) For which tasks is voice input most appropriate, gesture most appropriate, and direct manipulation most appropriate?

The use of redundant user inputs may seem unnecessary. Consider, however, a designer who is modeling human-VE interaction based on human-human communication, a recognized approach to human-computer interface design (Eberts, 1994). Redundant ‘inputs’ are often used in human-human communication, such as during a greeting where individuals simultaneously exchange verbal salutations and handshakes. In this case a verbal input is combined with a gesture for effective communication. Such redundant inputs could potentially be useful in HVEI. Redundant input capability could also support user preferences (i.e., some users may prefer verbal interaction, while others may favor direct manipulation). When providing redundant feedback it will be essential to consider the limitations of human-information processing (Card et al., 1983) to avoid sensorial overload. VE designers thus need to establish the most-effective command coordination schemes for their VE tasks.

Sensorial transposition occurs when a user receives feedback through other senses than those expected. This may occur because a VE designer’s command coordination scheme has substituted unavailable system sensory feedback (e.g., force feedback) with other modes of feedback (e.g., visual or auditory). Such substitution has been found to be feasible (e.g., Massimino & Sheridan, 1993, successfully substituted vibrotactile and auditory feedback for force feedback in a peg-in-hole task).

The sensorial substitution schemes may be one-for-one (e.g., sound for force, visual for force, visual for sound) or more complex (e.g., visual for force and auditory, visual and auditory for force) (Burdea & Coiffet, 1994). VE designers thus need to establish the most-effective sensorial transposition schemes for their VE tasks. The design of these substitutions schemes should be consistent throughout the virtual world to avoid sensorial confusion.

2.5 Virtual Environment Design Metaphors

It is known that well-designed metaphors can assist novice users in effectively performing tasks in human-computer interaction (Carroll & Mack, 1985). Designing effective VE metaphors could similarly enhance human performance in virtual worlds. Such metaphors may also be a means of assisting in the integration of multimodal interaction. For example, affordances may be designed that assist users in interacting with the virtual world much as they would interact with the multimodal real world. Affordances are the goals naturally furnished by an environment (Shaw, Kugler, & Kinsella-Shaw, 1990). They are the environmental properties that causally support goal-directed behavior. To be effective in managing human performance, VE affordance properties need to be represented by both an inflow of controllable human behavior and an outflow of detectable information (i.e., optic, haptic, olfactory flow pattern). Reactions to this information could then feed back into the cycle and direct the inflow of additional controlled human behavior. In this manner, environmental cues in a virtual world could elicit and direct the behavior of users. Well-designed affordances could reduce the perceived navigational complexity of a VE and enhance users' benchmark task performance. Unfortunately, at the present time many human-VE interface designers are using old affordances and metaphors (e.g., windows, toolbars), that may be inappropriate for HVEI.

Oren (1990) suggested that every new technology goes through an initial incunabular stage, where old forms continue to exist that may not be uniquely suited to the new medium. Virtual environments are in need of new design metaphors uniquely suited to their characteristics and requirements. McDowall (1994) has suggested that the design of interface metaphors may prove to be the most challenging area in VE development. VR sliders (3-D equivalents of scroll bars), map cubes (3-D maps that show space in a viewer's vicinity), and tow planes (where a viewer's navigation is tied to a virtual object that tows him/her about the VE) are all being investigated as potential visual metaphors for VEs. Portals and spirals are being investigated as potential replacements for windows (Laurel, 1994).

Beyond the need for new visual metaphors, VEs may also need auditory metaphors that provide a means of effectively presenting auditory information to users. Cohen (1992) has provided some insight into potential auditory metaphors through the development of "multidimensional audio windows" or MAWs. MAWs provide a conceptual model for organizing and controlling sound within traditional window-icon-menu-pointing device (WIMP) interfaces. Metaphors for haptic interaction may also be required. Limited work has been done in this area to date, and no noted haptic metaphors have been presented.

VE designers have, in the past, been guided by the design objects available in most 2-D toolkits (i.e., windows, icons, menus, pointing devices). Existing HCI guidelines are generally structured around the use of such toolkits (Dix et al., 1993). VE designers are not, however, bound by the limitations of such toolkits; they are rather bound by their creativity and design proficiency. With this freedom from toolkits, however, comes the loss of the associated guidance these constraints provide. Although VE designers will have virtually endless design possibilities, they also currently have limited guidance in designing effective human-virtual environment interfaces. Research into the design of new VE metaphors—and, more importantly, guidelines to develop such metaphors—is needed. Current HCI guidelines focus primarily on the visual metaphor. For example, Shneiderman (1992) provides design guidelines for data display and data entry, both primarily visually driven. VE design guidelines, however, will need to be multisensory, providing guidance for the design of visual, auditory and kinesthetic information. The key to the design of these new metaphors may be to identify expectations developed through real-world experiences in common and familiar environments and to use this knowledge to design consistent VE interaction metaphors (Ellis, 1993). This approach is an extension of the anthropomorphic approach that uses models of human-human communication to direct the design of human-computer interaction (Eberts, 1994). Using this approach, the constancies, expectations, and constraints elicited from interactions in the real world should be designed into VE metaphors, thereby potentially engendering a more intuitive interface design.

3 Health and Safety Issues in Virtual Environments

Maximizing human performance in VEs is essential to the success of this technology. Of equal importance is ensuring the health and welfare of users who interact with these environments. (See Figure 1.) If the human element in these systems is ignored or minimized, it could result in discomfort, harm, or even injury. It is essential that VE developers ensure that advances in VE technology do not come at the expense of human well-being.

There are several health and safety issues that may affect users of VEs. These issues include both direct and indirect effects. The direct effects can be looked at from a microscopic level (e.g., individual tissue) or a macroscopic level (e.g., trauma, sickness). The indirect effects include physiological aftereffects and psychological disturbances.

3.1 Direct Microscopic Effects

There are several microscopic direct effects that could affect the tissues of VE users. The eyes, which will be closely coupled to HMDs or other visual displays used in VEs, have the potential of being harmed. The eyes may be affected by the electromagnetic field (emf) of VEs if the exposure is sufficiently intense or prolonged (Viirre, 1994). Emf exposure could cause cataracts if the CRT used produces X-rays. Laser lights are also being considered for use in HMD and movement-detection systems. Standards exist for laser exposure that should be reviewed and adhered to by VE developers to minimize harm. In addition, eyestrain could be caused by poor adjustment of HMD displays, as well as flicker, glare, and other visual distortions (Ebenholtz, 1988, 1992; Konz, 1983; Sanders & McCormick, 1993). Mon-Williams, Wann, and Rushton (1993) found that, after subjects wore a binocular HMD with an IPD fixed to the mean of the subject group for ten minutes, they experienced a significant shift in vergence bias towards esophoria (inward turning of the eyes) during distance vision. A later study (Rushton et al., 1994) using the same procedure but a different biocular HMD (rather than the earlier binocular HMD that generated conflicts between depth cues presented by image disparity and image focal depth) found no significant problems for exposure durations of up to 30 minutes. These results indicate that, through careful HMD design, prismatic effects associated with incorrect IPD settings, poor illumination, poor contrast, and the close proximity of the working distance can be minimized. If not considered, however, these results indicate that significant visual stress from HMD exposure can occur and lead to ocular symptoms (e.g., unstable binocular vision and reduced visual acuity). Related visual aftereffects may engender an individual unsafe to interact with the real world (e.g., drive a car or ride a skateboard) after VE exposure.

There is concern over emf exposure (Viirre, 1994). It may be that mild emf exposure is harmless, but this has yet to be proven. Strong emfs could, on the other hand, cause cellular and genetic material damage in the brain as in other tissues. The issue is that at present we do not have a solid understanding of the effects of longterm emf exposure.

Phobic effects may result from VE use, such as claustrophobia (e.g., HMD enclosure) and anxiety (e.g., falling off a cliff in a virtual world). Viirre (1994) suggests, but has yet to prove, that no longterm phobic effects should result from HVEI, except potential avoidance of VE exposure.

The auditory system and inner ear could be adversely effected by VE exposure to high volume audio (e.g., the "Walkman" effect). One of the possible effects of such exposure is noise-induced hearing loss. Continuous exposure to high noise levels (particularly above 80 dBA) can lead to nerve deafness (Sanders & McCormick, 1993). The Occupational Safety and Health Administration (OSHA) has noise exposure limits that should be followed for VE design in order to prevent such hearing loss (OSHA, 1983).

Prolonged repetitive VE movements could also cause overuse injuries to the body (e.g., carpal tunnel syndrome, tenosynovitis, epicondylitis). The propensity for users to be inflicted by such ailments can be moderated by emphasizing ergonomics in VE design and judicious usage procedures.

The head, neck, and spine could be harmed by the weight or position of HMDs. DiZio and Lackner (1992) have observed that users who move about with HMDs weighing 2.5 pounds or more experience an increase in the inertia of head movements that could easily lead to movement injuries. In addition, this additional head weight often leads to symptoms of motion sickness.

3.2 Direct Macroscopic Effects

The risk of physical injury or trauma from VE interaction is of real concern. VE equipment is complex and interferes with normal sensory perception and body movements. Limited or eliminated vision of natural surroundings when wearing HMDs could lead to falls or trips that result in bumps and bruises. Sound cues may distract users causing them to fall while viewing virtual scenes. Imbalance of body position may occur due to the weight of VE equipment or tethers that link equipment to computers causing users to fall (Thomas & Stuart, 1992). Such tethers may not be visible in the virtual world, and thus could pose a threat to the safety of users. If haptic feedback systems fail, a user might be accidentally pinched, pulled, or otherwise harmed. Most force-feedback systems attenuate the transmitted force to avoid harm (Biocca, 1992a). As previously discussed, another direct macroscopic effect is that users may become motion sick (i.e., cybersickness) or potentially experience maladaptive physiological aftereffects from human-virtual environment interaction.

3.2.1 Cybersickness. One of the most important health and safety issues that may influence the advancement of VE technology is cybersickness. Cybersickness is a form of motion sickness that occurs as a result of exposure to VEs. Cybersickness poses a serious threat to the usability of VR systems. Users of VE systems may experience various levels of sickness ranging from a slight headache to an emetic response. Although there are many suggestions about the causes of cybersickness, to date there are no definitive predictive theories, although there are models in general. Research needs to be done in order to identify the specific causes of cybersickness and their interrelationships in order to develop methods that alleviate this malady. Without such an understanding cybersickness may remain a "snake" lingering in the underbrush of VE use and threatening the widespread diffusion of this technology (Biocca, 1992b).

There have been several factors identified that may contribute to cybersickness (e.g., vection, lag, field of view). Vection, a factor often associated with motion sickness, is the illusion of self-movement in a VE; when the body senses that there is no actual physical movement, a conflict occurs between the visual and vestibular systems which is believed to lead to sickness (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990). It has been suggested that this cue conflict can be resolved by adding a motion base to simulators. In a study conducted on helicopter pilots using both motion-base and fixed-base simulators, however, both groups of pilots became equally sick (McCauley & Sharkey, 1992).

In virtual systems, lag occurs when a user perceives a delay between the time a physical motion is made (e.g., turning the head to the right) and the time the computer responds with a corresponding change in the display. Such transport delays (i.e., lags) and asynchrony between two different inputs (e.g., visual and inertial) are often indicted in connection with cybersickness, but the data are sparse. Several have speculated that these distortions are the temporal analogies of spatial distortions and rearrangements that make people sick using mirrors and prisms (Kennedy, Lilienthal, Berbaum, Dunlap, Mulligan, & Funaro, 1987). The best evidence is that Navy simulators with the longest transport delays have the highest sickness rates. It has been hypothesized that asynchrony may be more provocative of sickness than lags. User adaptation to the VE should be rapid if the lags are constant or not at all if they are variable.

Both wide and narrow fields of view have been suggested to lead to motion sickness. Lestienne, Soechting and Berthoz (1977) found that subjects who viewed a wide field of view (FOV) experienced intense sensations of motion sickness. Nausea has also been found to occur, however, when the field of view is restricted (Anderson & Braunstein, 1985). Such experiments suggest that field of view may not be an overriding indicator of whether or not cybersickness is experienced. Howard, Ohmi, Simpson, and Landolt (1987) found that what is perceived as being in the distance drives vection which in turn often drives sickness. Since the peripheral FOV usually has been the main factor investigated for its effects on vection, perhaps depth per se needs to be studied as the vection and sickness driver.

The noted contradictory evidence among these motion sickness studies leads to skepticism about the actual impact of each of these factors. With the lack of definitive predictive theories, other potential solutions must be pursued. Mental rotation exercises have been cited as a means of identifying individuals who should be less susceptible to motion sickness and for potentially training others to improve their mental rotation capabilities, thereby moderating sickness (Parker & Harm, 1992). This approach may work as a screening device; however, based on studies of spatial orientation ability (Witkin, 1950), it is unlikely that those individuals low in spatial ability will acquire the capability to resolve inconsistencies in the relationships between virtual scene polarity and their internal body axes simply through mental rotation exercises. The reliability of tests that measure mental rotation ability (e.g., Ekstrom, French, & Harman, 1976) indicates that this aptitude is probably not readily learned, but rather an innate ability which each individual possesses to some degree.

One promising approach to moderating cybersickness is through the manipulation of the level of interactive control provided to users. Control may provide users with a means of adapting to or accommodating cue conflicts by building conditioned expectations through repeated interactions with a virtual world (e.g., when a user's head turns, the user learns to expect the world to follow milliseconds behind). Lack of control would not allow such expectations to be established since users would not be aware of which way they were turning at any particular moment (i.e., the course would be determined by the system).

Freedom of movement, or control, and its effect on cybersickness has not been adequately researched. Some studies imply that control may be a major factor influencing sickness. Reason and Diaz (1971) and Casali and Wierwille (1986) determined that crewmembers and copilots are more susceptible to sickness because they have little or no control over the simulators movements. Lackner (1990) suggested that the "driver" of a simulator becomes less sick than passengers because he/she can control or anticipate the motion. McCauley and Sharkey (1992) suggest that at "high altitudes and/or at lower speeds," freedom of movement will minimize cybersickness. Krueger (1991) has suggested that cybersickness may be modified by having individuals alternate between control and no-control situations. There is some empirical evidence to support the use of control as a moderator of cybersickness in virtual environments. Stanney and Hash (in press) conducted a VE study in which three levels of user-initiated control were examined (no control, complete control, and coupled control). The results indicated that the coupled control condition (i.e., in which the degrees of freedom of motion were matched to the needs of the task) produced significantly less sickness than the no-control and complete-control conditions.

Further study is needed to determine the exact nature of the relationship between control and cybersickness. The attractiveness of such a control theory, if proven, is that the level of user-initiated control could potentially be manipulated in order to alleviate the influences of other factors, such as vection and lag, in order to moderate sickness. Control also needs to be tested against varying degrees of other factors to see what level of freedom is necessary to potentially negate their effects. The research should focus on developing a general theory of cybersickness that would allow for the prediction of the combinations of factors that would be disruptive and lead to sickness, those that would be easy or hard to adapt to, and the relationship of these levels of adaptation to the level of user control. Such a theory would provide VE developers with the knowledge necessary to minimize the adverse effects of human-virtual environment interaction.

3.3 Indirect Effects

While cybersickness is a commonly cited concern of HVEI, a less-known yet equally or even more important indirect consequence of HVEI is the potential deleterious physiological aftereffects from VE exposure. The use of VEs may produce disturbing aftereffects, such as head spinning, postural ataxia, reduced eye-hand coordination, vestibular disturbances, and/or sickness. The plasticity of the human nervous system allows some individuals to adapt, becoming less ill with continued system interaction (Dolezal, 1982; Guedry, 1965; Welch, 1978). This adaptation is characterized by a decline in the initial response to an altered stimulus, development of an altered, often compensatory response following prolonged exposure to the change, and a continuation of the adapted response (i.e., an aftereffect) once the stimulus is removed (Parker & Parker, 1990). Such aftereffects have been known to persist for several hours after system exposure (Baltzley, Kennedy, Berbaum, Lilienthal, & Gower, 1989; Crosby & Kennedy, 1982; Ungs, 1987). Individuals who tend to remain sick and experience continued discomfort during VE interaction may actually have an advantage when returning to the normative conditions to which they remain physiologically suited.

Thus, while adaptation sounds advantageous because adaptive individuals become less ill with repeated exposure, the physiological modifications that elicit this adaptation are of concern. These physiological aftereffects may make individuals maladapted (i.e., at risk of injury) for the return to the real world once VE interaction concludes. Some of the most disturbing aftereffects include flashbacks, illusory climbing and turning sensations, perceived inversions of the visual field, reduced motor control (Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992; Rolland, Biocca, Barlow, & Kancherla, 1995), reduced complex psychomotor flexibility (Lampton et al., 1994), a disturbed vestibulo-ocular reflex (VOR) function (Hettinger, Berbaum, Kennedy, & Westra, 1987), postural disturbances (Kennedy, Fowlkes, & Lilienthal, 1993), and increased risk of adverse adaptations to subsequent normal environments (Regan, 1993).

The implication is that, with protracted or repeated exposures, those individuals who exit VE interactions feeling *less* affected (i.e., less ill) may actually be the ones at greatest risk. This was seen in studies of postural stability, where subjects' reports of motion sickness progressively diminished upon exiting over continued system interaction, while objectively measured ataxia worsened (Kennedy, Lanham, Drexler, & Lilienthal, 1995). Such aftereffects led the Navy and Marine Corps to institute grounding policies after simulator flights several years ago (Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989). Similar bans on driving, roof repair, or other machinery use after VE exposure may be necessary. Delayed effects from virtual experiences should also be investigated in order to ensure the safety of users once interaction with a virtual world concludes.

The existence of these aftereffects indicates that the primary approach to measuring the deleterious effects of VE interaction, i.e., subjective reports of motion sickness after VE exposure, may provide little indication of the reduction in physiological functioning actually experienced by individuals. For this reason more physiologically based tests are needed to objectively measure the aftereffects of VE exposure and to ensure the safety of users. Tests of postural stability have already been developed (Kennedy & Stanney, 1996). This measure can be employed before and after exposure to a VE system to certify that a user's balance upon exiting the system is at least demonstrably as good as it was upon entering. Current research is investigating the development of sensorimotor transformation (i.e., hand-eye coordination) tests of pointing errors induced by exposure to sensory conflicts in virtual environments (Kennedy, Stanney, Dunlap, & Jones, 1996).

Much as human-computer interactions were initially labeled "non-user friendly," if negative VE incidents occur, the technology could be branded "unsafe" and future use and proliferation of the technology could be hampered. The VE technology community should collaboratively establish health and safety standards that can direct and guide future developments. Creating and adhering to industry-wide health and safety standards should reduce harm to users as well as minimize potential liability risks of developers.

4 The Social Impact of Virtual Technology

While researchers are often concerned about human performance and health and safety issues when developing a new technology, an often-neglected indirect effect of new technologies is their potential social impact. (See Figure 1.) Virtual reality is a technology, which like its ancestors (e.g., television, computers, video games, and simulation) has the potential for negative social implications through misuse and abuse (Kallman, 1993). There is already a high level of concern over the negative influences of television and video games, which are much less interactive environments than VEs. Yet violence in VEs is nearly inevitable, one need only look at the violence in popular video games. Rather than waiting for these issues to arise in VEs, it might be prudent to address social issues before they result in crisis or harm.

Currently the potential negative social influences resulting from VE exposure are not well understood. For example, VE applications that are presented as benign forms of entertainment but which actually represent violence and destruction may become available at video game rooms in the near future. Such animated violence is already a known favorite over the portrayal of more benign emotions such as cooperation, friendship, or love (Sheridan, 1993). The concern is that users who engage in what seems like harmless violence in the virtual world may become desensitized to their violent virtual actions and then mimic that behavior in the look-alike real world. There is concern that virtual interactions could engender addiction and subtly condition violence.

There are many open issues (Stone, 1993; Whiteback, 1993), such as: What will be the psychological and character effects of VE use? How will interaction in the virtual world modify behavior? What will the "transfer of training" be for violent virtual interactions? Will individuals transfer violent virtual experiences to the real world? Will people turn their backs on the real world and become contented zombies wandering around synthetic worlds that fulfill their whims? Will VR users experience traumatic physical or psychological consequences due to a virtual interaction? Will people avoid reality and real social encounters with peers and become addicted to escapism? Is continual exposure to violent virtual worlds similar to military training, which through continued exposure may desensitize individuals to the acts of killing and maiming? How will VE influence young children who are particularly liable to psychological and moral influence? Does VE raise issues that are genuinely novel over past media due to the salience of the experience and the active interaction of the user?

Even with all of these concerns there is currently limited focus on the social implications of VE technology from its developers (Kallman, 1993). There are strong scientific reasons, however, why the active engagement available in VE games rather than the passive action of television watching can have better retention of learned skills. For example, Brunner (1966) demonstrated that learning-rich environments facilitate learning by embedding learners into a given environment (i.e., immersion) and allowing them to learn kinesthetically (i.e., actively) first. This learning-by-doing facilitates higher-level cognition and retention of the learned skills. The implication is that the continual act of virtual violence will facilitate a youth's ability to reason and think in the realm of violent behavior. For these same reasons, we should be concerned about the impact playing these games may have on the behavior of youth. To the extent that games similar to military combat are employed for recreational usage, then we may breed youth with social problems of some magnitude, ready, willing and able to commit violent acts. That the games are exciting, involving stress from immediate threats, the games may teach hasty, impulsive response rather than thoughtful consideration that is often needed to avoid violence by seeking alternatives.

Currently we do not know whether such violent behavior will result from VR gaming. While little systematic research has been performed in this area, the early data are not encouraging. In a recent study, HVEI was shown to significantly increase the physiological arousal and aggressive thoughts of young adults (Calvert & Tan, 1994). The study examined three theories:

(1) the arousal theory, which states that physiological responses (e.g., blood pressure, heart rate) to aggression should initially increase as users engage in a threatening experience, which can be channeled into aggressive activities similar to those that users are exposed to
(2) the social cognitive theory, which states that a user can become more aggressive after observing and then imitating aggressive acts—after enough exposure controls created to inhibit aggressive actions have become disinhibited or weakened
(3) the psychoanalytic theory, which states that a user will experience a subsequent decrease in aggression through catharsis as one releases aggressive drives safely in virtual rather than actual experiences.

The results of the study did not wholly support any one theory. The physiological arousal (i.e., heart rate) was a function of HVEI, however, hostile feelings did not increase as would be predicted by the arousal theory. Aggressive thoughts increased as a function of HVEI; however, a passive observational condition did not produce more aggression as would be predicted by the social cognitive theory. Unfortunately, neither aggressive thoughts nor hostile feelings decreased from baseline due to HVEI as would be predicted by the psychoanalytic theory, thus providing no support for catharsis.

The results indicate that physiological arousal and aggressive thought content may be significant predictors of HVEI. This increased negative stimulation may then be channeled into other activities in the real world. The concern is that VR immersion may potentially be a more-powerful perceptual experience than past, less-interactive technologies, thereby increasing the negative social impact of violent interactive technologies.

Research needs to be directed at developing a new conceptual model of the social implications of HVEI, potentially one that integrates the supported components of the arousal and social cognitive theories. Through such a model, the social consequences of HVEI may be predicted. There are problems with pursuing this research, including the lack of measures to quantify violent behavior, the considerable time needed to establish cause-effect relationships, and the difficulty of demonstrating a casual link outside of a laboratory setting. We have experienced difficulty in scientifically determining whether major factors such as poverty are causes of violent crime; it should prove no less of a challenge for VR technology. Worse yet, it could take a considerable amount of time to establish if there are any negative social implications from HVEI. Consider cigarette smoking, which was not linked to lung cancer or heart disease until after a generation of Americans had died in increasing numbers from these diseases. As for measures, while indirect measures such as those used by Calvert and Tan (1994) are available, a direct assessment of behavior changes with violent VR gaming is needed, but will predictably not become available very soon.

The concern is that violent VR gaming represents an unknown risk of increased violence in the next generation of our youth. A proactive approach is needed that weighs the risks and potential consequences associated with VE against the benefits. For example, the development of a VE system may improve the lives of several individuals (e.g., toy manufacturers, stockholders) yet harm others (e.g., children who become emotionally unhealthy due to excessive exposure to violent VR games). Waiting for the onset of harmful consequences should not be tolerated. Through a careful analysis, some of the problems of VEs may be anticipated and perhaps prevented. A proactive, rather than reactive, approach may allow researchers to identify and address potentially harmful side-effects related to the use of VE technology.

5 Conclusions

Computer speed and functionality, image processing, synthetic sound, and tracking mechanism have been joined together to provide realistic virtual worlds. Virtual reality is more than a sum of these components, however; it is inherently a system technology with an essential element being the user of the system. While the technology still needs perfecting, for VEs to be successful a fundamental advance requiring immediate attention is to determine how to effectively design the human-VE interface. The needs and abilities of VE users have not yet been adequately addressed in the design of virtual worlds. Since VE real-world applications are growing at a rapid rate, human-factors practitioners need to become involved before improper designs and practices become commonplace. This paper has structured human-factors research challenges into three primary areas within virtual environments: human performance efficiency, health and safety concerns, and social implications. Human-factors practitioners must take the lead in resolving these challenges to ensure that VE technology develops with adequate concern for its users.

While certainly not comprehensive, the extent of this paper is an indication of the number of variables that need to be considered when studying human factors issues in virtual environments. The level of human-factors effort needed to resolve these issues cannot be adequately addressed using traditional analysis techniques (i.e., selecting a few variables and performing an analysis using a completely randomized design). The issues with this approach include the fact that researchers have limited knowledge a priori of which variables are the most influential, and it would take a considerable amount of time to address all treatments in this manner. Instead, we believe that researchers should consider using fractional factorial designs. (See Jones & Kennedy, in preparation.) These designs permit the introduction of several variables at once, with relatively modest sample sizes ($n \cong 30$) in order to first screen lower-order effects (i.e., main effects and two-way interactions) while recognizing the confounding that occurs with higher-order terms. While the results of such experiments must be carefully interpreted, they provide an economic means of identifying the variables that have the greatest effect and that can subsequently be studied in more detail.

The HVEI field definitely requires that we be cross-disciplinary. The development of VE applications typically involves a team of professionals consisting of graphics designers to build 3-D models; sound specialists to create spatial audio effects; mechanical, electrical, and optical engineers to design and build interfaces for human-computer interaction (e.g., data gloves, exoskeletons); and computer programmers and scientists to write the code to control the complex simulations. We strongly recommend that human-factors personnel become part of the development team and evaluate virtual environments in terms of their use with human subjects. Such testing is very important in that there are, and will continue to be, large differences in VEs, and VEs will be used by many diverse populations.

As computers become more powerful, as display technologies permit the viewing of higher-quality images with greater FOVs, as techniques to experience haptic and force feedback become less costly, and as the creation of code to run and manage virtual environments is simplified, the use of virtual environments will expand at a rapid rate. Since these VEs will involve the interaction of people and machines, we need to apply human-factors principles to their design and use.

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