Realizing the Full Potential of Virtual Reality: Human Factors Issues That Could Stand in the Way

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ABSTRACT
This paper reviews several significant human factors issues that could stand in the way of virtual reality realizing its full potential. These issues involve maximizing human performance efficiency in virtual environments, minimizing health and safety issues, and circumventing potential social issues through proactive assessment.

KEYWORDS: human factors, human-virtual environment interaction

INTRODUCTION

Virtual reality (VR) technology will be used to advance many fields, including medicine, education, design, training, and entertainment. The reality is, however, a considerable amount of systematic research must be done before VR technology receives widespread use [10]. If VR systems are to be effective and well received by their users, researchers need to focus significant efforts on addressing a number of human factors issues [26]. This paper provides an overview of many of these human factors issues, including: human performance efficiency in virtual worlds; which is likely influenced by tasks characteristics, user characteristics, human sensory and motor physiology, multi-modal interaction, and the potential need for new design metaphors; health and safety issues, of which cybersickness may pose the most concern; and the social impact of the technology.

HUMAN PERFORMANCE EFFICIENCY IN VIRTUAL WORLDS

Computer speed and functionality, image processing, synthetic sound, and tracking mechanism have been joined together to provide realistic virtual worlds. A fundamental advance still required for virtual environments (VEs) to be effective is to determine how to maximize the efficiency of human task performance in virtual worlds. 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, then further pursuit of this technology may be fruitless. Focusing on understanding how humans can perform most effectively in VEs is thus of primary importance in advancing this technology.

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 multi-modal interaction; and the potential need for new visual, auditory and haptic design metaphors uniquely suited to virtual environments.

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. It is important to determine the types of tasks for which VEs will be appropriate. In order to obtain this understanding the relationship between task characteristics and the corresponding virtual environment characteristics which effectively support their performance (e.g., stereoscopic 3D visualization, real-time interactivity, immersion, etc.) must be attained.

While there is limited research on the types of task characteristics that are uniquely suited to human-virtual environment interaction (HVEI) (a notable exception is [29]), there is extensive literature on task characteristics in general. In order to identify tasks which are appropriate for virtual environment training, this body of knowledge on task characteristics must be explored and its relation to virtual task performance needs to be identified. For example, task characteristics which lend themselves to

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perceptual understanding through three-dimensional visualization in a virtual world should be distinguished. Bennett, Toms, and Woods (1993) research supports the use of such 3D displays for tasks requiring information integration. On the other hand, focused attention tasks tend to be more effectively performed using 2D displays. Thus, displaying such tasks in 3D stereoscopic virtual worlds could potentially hinder performance.

Task characteristics which are suitable for representation as displayable virtual objects which can be manipulated through perceptual and motor processes also need to be determined. For example, Sollenberger and Milgram (1993) found optimal path tracking performance when using a 3D, rotating, stereoscopic display. Texturing, the surface rendering available on virtual objects, has been found to be effective for representing additional data dimensions, such as emergent features. These relationships need to be further explored in order to clearly delineate the specific characteristics of virtual worlds which support and enhance task performance as compared to other visualization approaches such as real-time simulations, animations, and non-interactive three-dimensional visualizations.

A taxonomy of virtual task characteristics would be instrumental in providing designers with a tool to guide and direct their design efforts in order to maximize human performance. Such a tool would classify tasks according to the types of information displays (e.g., 2D, 3D stereoscopic, point, line, angle, area, volume, etc.) and interactions (e.g., passive, enactive, interactive) which maximize human-performance efficiency in virtual worlds. The influences of user characteristics (e.g., high versus low spatial individuals) would also need to be considered. Such a taxonomy could assist in guiding VE designers by imposing order [23] on the complex interactions between user, task, and system phenomena.

User Characteristics

An important aspect influencing human VE performance is the affect of user differences. Significant individual performance differences have already been noted in early studies [13]. User characteristics that significantly influence VR experiences need to be identified in order to design VR systems that accommodate the unique needs of users. In order to determine which user characteristics are influential in VEs one can examine studies in human-computer interaction (HCI). In HCI one of the primary user characteristics which interface designers adapt to is level of experience. Experience level influences the skills of the user, the abilities which predict performance, and the manner in which users understand and organize task information [6]. In examining the influences of experience on HVEI, one could thus 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. The implication being that designers must design the VE interface to be appropriate for the level of expertise of the target user population. Understanding what is an "appropriate" VE interface for novices versus experts is a challenge.

Technical aptitudes (e.g., spatial visualization, orientation, spatial memory, spatial scanning) are generally significant in predicting HCI performance [6]. These studies indicate 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 are particularly related to system navigation issues -- users often report being "lost" within hierarchical menu systems [21]. These findings are particularly relevant to VEs which may often place a high demand on navigation skills. In fact, users are already known to become lost in virtual worlds [18]. The issue is thus how to assist low spatial users with maintaining spatial orientation within virtual worlds. New design metaphors could potentially be developed to assist with this issue.

Other aptitudes, such as verbal and motor ability, and traits, such as personality, that have not been found to consistently predict human computer performance [6], may become more influential during HVEI. Particularly with the emphasis on audio and haptic interaction modes in VEs [10, 14], it is essential that human factors analysis be devoted to understanding the influences of these other aptitudes on HVEI.

Design Constraints Imposed by Human Sensory and Motor Physiology

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 the multi-modal interactions provided by VE systems will not be compatible with their users. Such design incompatibilities could place artificial limits on human VE performance. VE design requirements and constraints aimed at maximizing human VE performance should thus be developed by taking into consideration the abilities and limitations of humans [10]. The physiological and perceptual issues which directly impact the design of multi-modal VEs, include: visual perception, auditory perception, and haptic perception.

Visual Perception. The design of visual presentations for VEs is complicated because the human visual system is

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very sensitive to any anomalies in perceived imagery, especially in motion scenes [14]. During virtual motion scenes, minute, nearly imperceptible scene anomalies become dreadfully apparent because of the unnatural appearance of visual flow field cues [10]. In order to avoid this issue, more research is needed to develop guidelines that assist designers in fabricating approximate optical flow patterns. In general, human visual perception needs to be better understood in order to ensure that the most effective visual scenes are developed for virtual worlds.

It is also important to determine what a viewer can see in a VE, that is to determine the viewer's visual field when wearing a Head Mounted Display (HMD). In order to determine exactly what individuals can see in HMDs, visual field graphical dimensions must be overlaid onto obscuration plots imposed by HMDs. HMDs substantially reduce the field of view (FOV) of a user, thus obscuring the perception of motion in the peripheral vision. Current systems are generally limited to a FOV of 70 degrees per eye and do not provide peripheral vision [14]. Kalawsky (1993) has suggested, but not yet proven, that many virtual tasks will require FOVs of 100 degrees or more in order to achieve immersive environments. These suggestions needed to be further studied in order to determine what FOV is required to perform different kinds of virtual tasks effectively. Then the extent to which FOVs need to be enlarged can be specified.

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. Although it is known that audio localization is primarily determined by intensity differences and temporal or phase differences between signals at the ears, such localization is affected by the presence of other sounds and the direction from which these sounds originate [10]. In addition, while auditory localization is understood in the horizontal plane (left to right), localization in the median plane (intersection between front and back) and discrimination of sounds from front to back are not well understood. Thus, much work is needed in order to effectively synthesize 3D auditory environments.

In order to study 3-D audio localization, binaural localization cues received by the ears can be represented by a Head Related Transfer Function (HRTF), phase differences, and overtones [5]. The HRTF represents 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. Personalized HRTFs may need to be developed because these functions are dependent on the physiological makeup of each individual listener's ear. Ideally, a more generalized HRTF could be designed that would be applicable to a multitude of users.

Haptic Perception. A haptic sensation (i.e., touch) is a mechanical contact with the skin [10]. Three mechanical stimuli produce the sensation of touch: a displacement of the skin over an extended period of time; a transitory (few millisecond) displacement of the skin; and a transitory displacement of the skin which is repeated at a constant or variable frequency. Even with this understanding of 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 which are all a function of the type and position of the mechanical stimuli. 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. Surface characteristics of the stimulus (e.g., hard, soft, textured) also influence the sensation of touch.

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 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.

Integration Issues with Multi-Modal 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 multi-modal interaction. One of the aspects that makes VEs unique from other interactive technologies is its ability to present the user with multiple inputs and outputs. This multi-modal 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 can enhance human performance in virtual worlds [16]. There is currently, however, a limited understanding on how to effectively provide such sensorial parallelism [3]. When

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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 (1) the coordination between sensing and user command and (2) the transposition of senses in the feedback loop.

Command coordination considers the user input as primarily mono-modal (e.g., through gesture or voice) and feedback to the user as multi-modal (i.e., any combination of visual, auditory, 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 mouse at the same time as directing a search via voice input); and (3) for which tasks is voice input most appropriate, gesture most appropriate, and direct manipulation most appropriate.

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 and Sheridan (1993) successfully substituted vibrotacticle and auditory feedback for force feedback in a peg-in-hole task). VE designers thus need to establish the most effective sensorial transposition schemes for their virtual tasks. The design of these substitutions schemes should be consistent throughout the virtual world to avoid sensorial confusion.

Virtual Environment Design Metaphors

It is known that well-designed metaphors can assist novice users in effectively performing tasks in human-computer interaction [4]. Thus, 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 multi-modal interaction. For example, affordances may be designed that assist users in interacting with the virtual world much as they would interact with the multi-modal real world. Unfortunately, at the present time many human-VE interface designers are using old 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 which may not be uniquely suited to the new medium. Currently, virtual technology appears to be in such a stage. For example, many users of virtual environments don their high tech helmet and gloves and enter the virtual world only to find floating menus awaiting them! 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 (3D equivalents of scroll bars), map cubes (3D maps which show space in a viewer's vicinity), and tow planes (where a viewer's navigation is tied to a virtual object which tows him/her about the VE) are all being investigated as potential visual metaphors for virtual environments.

Beyond the need for new visual metaphors, VEs may also need auditory metaphors which 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 MAW. MAW provides a conceptual model for organizing and controlling sound within traditional window-icon-menu-pointing device (WIMP) interfaces. In addition, Hahn, Gritz, Darken, Geigel, and Won Lee (1993) have developed the concept of 'timbre trees' which are general representations of sound. Hahn et al. (1993) suggest that timbre trees can be used as a construction methodology for representing any new synthetic sound.

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.

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. 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 cost of human well being.

There are several health and safety issues which may affect users of VEs. These issues include both direct and indirect affects [27]. The direct effects can be looked at from a microscopic level (e.g., individual tissue) or a macroscopic level (e.g., trauma). The indirect effects are primarily psychological.

There are several microscopic direct effects which could affect the tissues of VE users. The eyes, which will be closely coupled to HMDs or other visual displays used in

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VEs, have the potential of being harmed. The central nervous system (CNS) could be affected by the emfs of VE systems.

Some individuals are susceptible to "flicker vertigo" -- when they are exposed to flickering lights (usually in the range of 8 to 12 Hz) they experience a seizure. VE displays flickering at this rate could lead to a seizure in a few users, even in some unaware that they have the condition.

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 long term phobic effects should result from HVEI, except potential avoidance of VE exposure.

The auditory system and inner ear could be adversely affected by VE exposure to high volume audio (e.g., the "Walkman" effect). One of the possible affects of such exposure is noise induced hearing loss. Prolonged repetitive VE movements could also cause overuse injuries to the body (e.g., carpal tunnel syndrome, tenosynovitis, epicondylitis). The head, neck and spine could be harmed by the weight or position of HMDs [10, 27].

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 [26, 27]. Obstacles in the real world, that may not be visible in the virtual world, could pose a threat to the safety of users. If haptic feedback systems fail a user might be accidentally pinched, pulled or otherwise harmed. Another direct macroscopic effect that could prevent VR from realizing its full potential is that many users of VEs experience motion sickness (i.e., cybersickness). Such sickness may prevent users from seeking further VE interactions.

The use of VEs may produce disturbing after-effects, such as head spinning and delayed onset of sickness. Delayed effects from virtual experiences must be investigated in order to ensure the safety of users once interaction with a virtual world concludes.

If a system fails, the sudden disruption of "presence" may cause disorientation, discomfort, and/or harm. Finally, psychological or emotional well-being could be negatively influenced by VE interaction (e.g., addiction, transfer- of-training from violent VEs). All of these health and safety issues must be addressed in order to ensure the well being of users interacting with virtual worlds.

Cybersickness

One of the most important health and safety issues that may influence the advancement of VE technology is cybersickness. Cybersickness (CS) is a form of motion sickness that occurs as a result of exposure to VEs. Cybersickness poses a serious threat to the usability of VE systems. Users of VE systems generally experience various levels of sickness ranging from headaches to severe nausea [10]. Although there are many suggestions about the causes of motion sickness, to date there are no definitive theories of cybersickness. Research needs to be done in order to identify the specific causes of CS and their inter-relationships in order to develop methods which alleviate this malady. If CS is not adequately addressed, many individuals may avert VE experiences in order to avoid becoming sick.

Motion sickness is considered to be the product of a cue conflict acting upon the visual and/or vestibular systems [9]. The user's body perceives this conflict as a poison and attempts to remove this "poison" by making itself sick [19]. Motion sickness may manifest itself in the form of headaches, blurred vision, salivation, burping, eye strain, dizziness, vertigo, disorientation, or even severe vomiting. It has been shown that between 10 to 60% of users demonstrate some form of simulator sickness [12]. For those who do become sick, research has shown that CS may prevent a person from wanting to reenter a virtual world [1]. Currently, however, system developers cannot prevent such sickness from occurring because the exact causes of motion sickness are not well defined.

While it is known that users adapt to VE experiences and become less sick over time [8], the first impressions of users may influence their attitudes towards this technology. If users become very ill during their initial experience, they may avoid future VE interactions. Relying on adaptation alone as a remedy for CS may thus not prove effective.

There have been several studies focused on understanding the factors that may contribute to motion sickness (e.g., vection, lag, field of view, etc.), yet no general theory of motion sickness has resulted from this research. In fact, contradictory evidence among the existing studies leads to skepticism about the actual impact of each of these factors. The reason for these contradictions may be due to the fact that in some of these studies users were in control of their moment about the simulated world, while in others they were confined to a predestined course. Control may provide users with a means of adapting to or accommodating cue conflicts by building conditioned

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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). Thus, without control, users would not be expected to adapt to cue conflicts. User control in conjunction with adaptation may provide a means of minimizing the influences of cybersickness.

Research on CS needs to be conducted in order to fully specify the relationships between control, adaptation, and CS. Control also needs to be tested against varying degrees of other factors to see what level of freedom is necessary to potentially negate their affects. The research should focus on developing a general theory of CS which would allow for the prediction of the combinations of factors which would be disruptive and lead to CS; those which 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 VE interaction.

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 times neglected effect of new technologies is their potential social impact. Virtual reality is a technology, which like its ancestors (e.g., television, computers, video games) has the potential for negative social implications through misuse and abuse [11]. Its higher level of user interaction may even pose a greater threat than past technologies. 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. Such an approach requires that researchers and developers prioritize social issues early on in VE development, rather than taking a wait-and-see attitude. Most VR conferences have yet to even recognize and address that social issues may exist.

Currently the potential negative social influences resulting from VE exposure are not well understood. There are many open issues [11, 22, 25, 28], 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 which fulfill their whims but disregard their growth as a human being? 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? Could the behaviors of soldiers after intense military training events provide an indication of the influences of intense violent VE interactions? How will VE influence young children who are particularly liable to psychological and moral influence? Does VE raise issues which are genuinely novel over past media due to the salience of the experience and the active interaction of the user? These issues need to be proactively explored in order to circumvent negative social consequences from HVEI.

CONCLUSIONS

This paper has presented many of the human factors issues which must be addressed in order for VR technology to reach its full potential without inflicting harm along the way. VR technology promises to permeate both professional and personal aspects of our lives. If this influx is to be a positive influence rather than a forceful intrusion, it is essential that each of these human factors issues receive significant systematic research.

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