

Human Factors Consideration in Clinical Applications of Virtual Reality

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Abstract. Virtual reality environments have many potential applications in medicine, including surgical training, tele-operated robotic surgery, assessment and rehabilitation of behavioural and neurological disorders and diagnosis, therapy and rehabilitation of physical disabilities.

Although there is much potential for the use of immersive virtual reality environments in clinical applications, there are problems which could limit their ultimate usability. Some users have experienced side-effects during and after exposure to virtual reality environments. The symptoms include ocular problems, disorientation and balance disturbances, and nausea. Susceptibility to side-effects can be affected by age, ethnicity, experience, gender and physical fitness, as well as the characteristics of the display, the virtual environment and the tasks.

The characteristics of the virtual reality system have also been shown to affect the ability of users to perform tasks in a virtual environment. Many of these effects can be attributed to delays between the sampling of head and limb positions and the presentation of an appropriate image on the display.

The introduction of patients to virtual reality environments, for assessment, therapy or rehabilitation, raises particular safety and ethical issues. Patients exposed to virtual reality environments for assessment and rehabilitation may have disabilities which increase their susceptibility to certain side-effects. Special precautions therefore need to be taken to ensure the safety and effectiveness of such virtual reality applications.

These precautions include minimisation of possible side-effects at the design stage. Factors are identified which are likely to affect the incidence of side-effects during and after exposures, and which need to be understood in order to minimise undesirable consequences. There is also a need for the establishment of protocols for monitoring and controlling exposures of patients to virtual reality environments. Issues are identified which need to be included in such protocols.

1. Introduction

There is some debate in the literature concerning what constitutes a virtual reality environment [1]. In this paper, a virtual reality environment is considered to be a three-dimensional, real-time graphical environment synthesised by a computer, in which the viewpoint or the orientation of displayed objects are controlled by the user via body position sensors or user-input devices.

The virtual environment may be displayed on a desktop monitor, a wide field-of-view display such as a projection screen, or on a head-mounted display. A wide field-of-view display is employed give the user an illusion of spatial immersion, or presence, within the

virtual environment. A virtual environment displayed on a wide field-of-view display which is fixed in space is referred to as partially immersive virtual reality. A fully immersive virtual reality environment utilises a head-mounted display, with a head position sensor to control the displayed images so that they appear to remain stable in space when turning the head or moving through the virtual environment. A see-through head-mounted display and head position sensor may be employed to augment the user's experience of the real world by superimposing space-stabilised computer-generated images of virtual objects on the user's view of the outside world.

1.1 Clinical applications of virtual reality

Virtual reality environments are being developed for a number of different clinical applications including surgical training and the assessment and rehabilitation of patients suffering from a range of disorders.

1.1.1 Surgical simulation training and assistance

Surgical simulators are being developed to train surgeons in new procedures such as in minimally invasive surgical techniques. Minimally invasive, endoscopic surgery allows many operations to be performed on patients through small incisions, resulting in minimal damage to surrounding tissue and muscles. The surgeon views the site of the operation on a video monitor, via an endoscope which is inserted into the incision. The operation is performed using special instruments which are inserted into the incision through long tubes. The surgeon is presented with a complex motor task, using visual and force feedback. Several authors [2,3,4] have proposed the development of simulators for training surgeons in the use of such techniques determining their level of competence before they operate on patients. Hunter *et al* [5] have described an application of virtual reality to control a microsurgical robot, for use in ophthalmic surgery. The objective of the system is to enhance the accuracy and dexterity of a surgeon by enhancing and augmenting images visual images, filtering hand tremor and performing safety checks.

1.1.2 Assessment and rehabilitation of behavioural and neurological disorders.

Immersive virtual reality environments have been investigated for desensitisation in the treatment of agoraphobia and fear of heights [6,7]. The graded exposure to virtual anxiety-producing stimuli was shown to be effective in reducing the degree of anxiety. It has been suggested that virtual environments may be used to overcome some difficulties in traditional systematic desensitisation treatments such as providing stimuli for patients who have difficulty imagining situations but who are too phobic to face real situations. Riva [8] has described an immersive virtual reality environment for treatment of body image disturbances and body dissatisfaction associated with eating disorders. The treatment involves exposing subjects to reflected and altered images of their own body and presentation of visual-motor tasks involving virtual objects such as weighing scales. The effectiveness of such applications is assumed to rely on patients having a strong sense of presence within the virtual environment.

Virtual environments may be used to measure cognitive function in a realistic everyday setting, but with the ability to maintain strict control over all aspects of the situation including potential hazards [9]. Strickland [10] has described a virtual reality application

designed to provide a safe, customised learning environment for children with autism. Autistic individuals have a distorted perception of the external world. The virtual reality environment allows a controlled distortion of the environment in order to better match the expectations of the individual.

1.1.4 Applications for diagnosis, therapy and rehabilitation of physical disabilities.

Kuhlen and Dohle [11] have suggested that patients suffering from motor disturbances can benefit from virtual reality environments in various ways. These include the re-training of disturbed functions in a series of graded motor tasks of increasing complexity. Precise feedback of success can be provided in real time. Applications have been described for analysis and diagnosis of movement disorders [11]. One application enables trajectories recorded during patients' motor tasks to be visualised by a physician in three dimensions. The three-dimensional trajectories can be animated and observed from different viewpoints. For rehabilitation of certain movement disorders patients may be presented with virtual environments in which visual cues are strongly distorted, so as to encourage patients to rely more on neglected sensory information.

1.2 Human factors problems with virtual reality applications

Although there is much potential for the use of virtual reality in areas such as those described above, human factors problems have been encountered with some virtual reality applications which could limit their ultimate usability.

Some users have experienced side-effects during and after exposure to virtual reality environments, including:

- ocular problems, such as eyestrain and blurred vision;
- disorientation and balance disturbances;
- nausea;

Problems of disorientation, balance and nausea in virtual reality environments have been ascribed to temporal and spatial distortions between actual motions of the user's body and corresponding movements of displayed images. Such distortions have also been shown to degrade the performance of tracking, manipulation and reading tasks, and to reduce the strength of presence and realism in interactive immersive virtual environments.

The known problems of virtual reality environments could lead to:

- compromised safety and health through visual and postural disturbances such when driving or performing demanding activities following exposure;
- compromised learning: symptoms may interfere with the learning of skills in a virtual environment through distraction, or unnatural perceptual-motor strategies may be adopted to avoid side-effects, leading to negative transfer of training;
- lack of confidence in the virtual environment leading to decreased use.

The introduction of patients to virtual reality environments, for assessment, therapy or rehabilitation, raises particular safety and ethical issues. Whalley [12] has suggested that research programmes that fail to take proper account of the ethical issues surrounding exposures of patients to such new technologies are likely to encounter practical constraints on their development which delay the improved understanding of disease and the

introduction of improved treatments. Strategies need to be defined to detect any adverse effects of treatments, some of which may be difficult to anticipate, at an early stage.

This chapter identifies side-effects which have been reported during or following exposures to simulators and virtual reality environments, and factors which are likely to affect the incidence of these side-effects. These factors need to be considered in the design of clinical applications in order to minimise undesirable consequences. Suggestions are made for the establishment of protocols for monitoring and controlling exposures of patients to virtual reality applications for assessment and rehabilitation. A need is identified for more fundamental systematic research so as to improve understanding of the interaction between different factors influencing side-effects.

2. Side Effects of Exposures to Virtual Reality Environments

Users of virtual reality environments have reported side-effects similar to those which have been reported during and after exposures to simulators with wide field-of-view and head-coupled displays [15-21]. These side-effects have been collectively referred to as “simulator sickness” [13,14]. Simulator sickness is characterised by three classes of symptoms, as shown in Table 1 [21,22].

Table 1. Symptoms reported during and after exposure to simulators and virtual reality environments

Oculomotor	Disorientation	Nausea
<ul style="list-style-type: none"> • headache • diplopia (double vision) • blurred vision • • eyestrain • difficulty in focusing • visual fatigue 	<ul style="list-style-type: none"> • dizziness • vertigo • postural instability • degraded psychomotor performance 	<ul style="list-style-type: none"> • drowsiness • increased salivation • sweating • stomach awareness • loss of appetite • burping • • vomiting

One study of simulator sickness symptoms has shown that in 25% of subjects reporting symptoms, the symptoms lasted for more than one hour after exposure. In 8% of the subjects they lasted for more than 6 hours [23]. In another study, some symptoms were experienced by a small number of subjects more than 24 hours after simulator training [24].

Concern has been expressed over possible behavioural and social consequences of repeated exposure to virtual reality such as hallucinations and addiction. However, these are largely speculative and as yet unsupported by scientific evidence [17].

2.1 Causes of disorientation, loss of balance and nausea in virtual reality environments.

Disorientation and nausea in simulators and virtual reality systems are similar to some of the symptoms of motion sickness and both are generally considered to be caused by

conflicts between the information received from two or more sensory systems [25]. Sensory conflict alone is not sufficient to explain the development of simulator sickness, since it cannot account for the capability of the human body to adapt to provocative stimuli. To take account of habituation, the concept of sensory conflict has been extended into a theory of sensory rearrangement [25] which states that: “all situations which provoke motion sickness are characterised by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular system and the non-vestibular proprioceptors are at variance either with one another or with what is expected from previous experience”.

There are commonly assumed to be two main categories of sensory conflict which can cause motion sickness: inter-modality rearrangements (between the eyes and the vestibular receptors) and intra-modality rearrangements (between the semi-circular canals and the otoliths in the vestibular system). Lags between head movements in an immersive virtual reality environment and the corresponding movement of the displayed images are one source of conflict between visual and vestibular perception of self-motion (i.e. motion of the observer's own body). Self-motion can be perceived by visual, vestibular and somatosensory mechanisms [26]. Self-motion is normally estimated by combining complementary visual and vestibular cues: low frequency visual cues are used to augment higher frequency vestibular cues, giving the capability of sensing head motion over a range of different head motions [27].

In the absence of head motion, illusions of self-motion can be produced by moving images on a display. Illusions of rotational self-rotation, caused by rotating scenes, are referred to as circularvection. Illusions of translational self-motion, caused by scenes moving in a flat plane, are referred to as linearvection. Illusions of self-motion can also be induced by somatosensory mechanisms, such as when walking in the dark, on a rotating platform, in the opposite direction to the platform motion [26].

When visual and vestibular motion cues are both present, there can be a non-linear interaction whereby conflicts between expected visual and vestibular cues, especially those involving direction disparities, result in a precipitous decline in visually-inducedvection and a temporary domination by the vestibular response [28]. Experimental work by Zacharias and Young [27], has shown that when the conflict between visual and vestibular signals is high, the relative weighting given to the vestibular input increases. The effect of this adjustment is to emphasise visual signals when the vestibular signals are either highly variable or unlikely to present meaningful information on the slow changes in true body velocity. When sudden changes in visual field velocity are not in agreement with vestibular signals, then the visually induced motion is largely ignored in favour of reliance on the vestibular cues. When a visual surround begins to rotate in the absence of real accelerations of the head, the surround will often be initially perceived as moving and it may take several seconds for the illusion of self-motion to become established. The latency for the onset of circularvection has been shown to decrease with decreasing acceleration of the visual field down to about 5 degrees/second [26]. Rearrangements between vestibular and visual signals can occur when:

- there is visual stimulation in the absence of vestibular stimulation;
- there is a delay between head motions and corresponding movements of a visual scene;
- the motions of a visual scene are distorted compared with corresponding movements of the head.

Vection has been shown to be highly nauseogenic [29-31]. Vection has also been shown to induce inappropriate postural adjustments in experimental subjects. Subjects incline themselves in the same direction as the movement of the visual scene movement, with a latency of between 1 and 2.5 s, and an after-effect on the cessation of motion. The amplitude of the postural adjustments are proportional to the image velocity [32,33]. Subjects also sway in synchrony with the motions of an oscillating visual surround. In adult subjects with normal vestibular function, the effects of movements of a visual scene on postural sway are likely to be greatest when the frequency of the motion is around 0.1 Hz [34]. Postural stability is normally controlled by a combination of visual, vestibular and somatosensory feedback. Disturbances of any of these sensory mechanisms leads to increased amplitudes of postural sway and an increased risk of falling [35]. Subjects with a history of vestibular dysfunction, and young children, are likely to be more dependent on visual cues for maintaining postural stability. In such subjects, the destabilising effects of an oscillating visual surround are greater, and extend to higher frequencies than in normal adults [26,34].

2.2 Ocular problems following exposure to virtual reality

The most commonly reported symptom of simulator sickness is eyestrain [16]. Eyestrain is likely to result from the inability of the oculomotor system to correct small errors or disruptions in oculomotor subsystems [36].

Table 2. Factors contributing to simulator sickness in virtual environments

User characteristics	System characteristics	Task characteristics
<i>physical characteristics of user</i> <ul style="list-style-type: none"> • age • gender • ethnic origin • postural stability • state of health and fitness • medication 	<i>display</i> <ul style="list-style-type: none"> • contrast • luminance level • resolution • phosphor lag • refresh rate • flicker • inter-ocular distance 	<i>movement through virtual environment</i> <ul style="list-style-type: none"> • control of movement • speed of movement
<i>experience of user</i> <ul style="list-style-type: none"> • exposure to the virtual reality system • motion sickness history 		<i>visual image</i> <ul style="list-style-type: none"> • field of view • scene content • image motion • viewing region • visual flow
<i>perceptual factors and personality</i> <ul style="list-style-type: none"> • adaptivity and receptivity • neurotiscm 	<i>system lags</i> <ul style="list-style-type: none"> • time delay • update rate 	<i>interaction between VE and user</i> <ul style="list-style-type: none"> • head movements • posture

Head-mounted displays appear to have particular potential to produce short term oculomotor symptoms. Mon-Williams *et al* [21] have suggested that the designs of

currently available liquid-crystal display (LCD) head-mounted displays do not take sufficient account of ophthalmic and physiological factors and generally produce poor quality images, with low illumination levels, poor contrast and uncertain binocular alignment. A ten-minute immersion in a virtual environment, involving a task which required subjects to scan and attend to detail in the displayed image, was sufficient to produce oculomotor symptoms (see Table 1) in 12 out of the 20 subjects. Tests of visual function before and after immersion revealed short-term changes consistent with disruption of the accommodation/convergence system and a general disruption of fine binocular fusion. There was also a reduction in visual acuity in four subjects. Concern was expressed about possible long term oculomotor effects on individuals, particularly children, with unstable binocular fusion. There are also potential short-term dangers for users who attempt to drive or perform other potentially hazardous tasks while still suffering from unstable binocular vision or decreased visual acuity.

A later study by the same authors [37] indicated that many of the above problems might be avoided by relatively simple design changes to a head-mounted display. These changes allow adjustments to the inter-ocular distance, to match differences in users' inter pupillary distances, and to the focal length of the optics to correct for differences between the focal lengths of each image due to manufacturing tolerances.

2.3 Factors influencing side-effects of virtual reality environments

Factors which have been identified as contributors to simulator sickness and similar side-effects in virtual reality systems are shown in Table 2 [21, 38-40]. These are divided into characteristics of the user, the system and the task. Few systematic studies have been carried out to determine the effects of the characteristics of virtual reality systems and of user characteristics on the symptoms of simulator sickness. Hence, some of the evidence for the possible influences of these factors has been inferred from studies of visually-induced motion sickness and other symptoms and of motion-induced sickness (i.e. sickness caused by vehicle motions), as well as observations of effects of exposures in simulators.

2.4 Physical characteristics of user

2.4.1 Age

Age has been shown to have a large effect on susceptibility to motion-induced motion sickness. Motion sickness susceptibility is greatest between the ages of 2 and 12 years. Susceptibility tends to decrease rapidly from 12 to 21 years, then more slowly through the remainder of life [25]. Age also influences postural imbalance induced by motions of a visual scene. Young children tend to fall over in the direction of any motion of the visual scene, the effects of visual motion slowly decreasing above the age of about five years [26].

2.4.2 Gender

Females have been shown to be generally more susceptible than males to sickness induced by vehicle motions. It is unclear whether the differences are due to anatomical differences or an effect of hormones [41]. In a study of sea-sickness among 20,029 passengers on ships [41,42], sickness data were obtained by questionnaire during 114

different voyages on nine different vessels (including two hovercraft and one hydrofoil). More than 20,000 questionnaire responses were obtained, showing that vomiting occurred among 8.8% of female passengers and 5.0 % of male passengers. Of the female passengers, 33.7% indicated that they felt unwell compared with 24.7% of male passengers. The differences between males and females may be greater in some environments. In a study of 3,256 coach passengers females were more likely to vomit than males by a ratio of three to one. In a study of 923 aircraft passengers females were found to be more likely to vomit by a ratio of five to one. Females may have an increased susceptibility during menstruation or pregnancy [25].

2.4.3 Ethnic origin

There is some evidence that ethnic origin may affect susceptibility to visually-induced motion sickness. In one experiment a sample of Chinese women showed significantly greater disturbances in gastric activity and reported significantly more severe motion sickness symptoms than European-American or African-American women when exposed to a rotating optokinetic drum. It is unclear whether this effect was due to environmental or genetic factors [43].

2.4.4 Postural stability (upright balance)

Postural instability is a widely reported result of exposure simulators [15,16,23,24]. Kolasinski [29] has suggested that individuals who are less stable before exposure to simulators and immersive virtual reality environments may be more susceptible to disorientation and nausea during or after exposure. The evidence for this was derived from a survey of military pilots, all of whom could be expected to have normal vestibular function. In the general population poor scores in balance tests, particularly when visual feedback is disrupted [35], may be an indicator of vestibular dysfunction, making a subject more dependent on visual cues for maintaining postural stability. Such a subject will also be more susceptible to the destabilising effects ofvection, induced by a moving visual surround [32,33], and may be at risk from falling when viewing large moving scenes. Labyrinthine-defective individuals (i.e. with non-working vestibular apparatus) are immune from motion sickness symptoms.

2.4.5 State of health and fitness

The state of health of an individual may affect susceptibility to simulator sickness. It has been recommended that individuals should not be exposed to virtual reality environments when they are not in their usual state of fitness due to illness, including flu or ear infections, hangover, sleep loss or when taking medications that may affect visual or vestibular function [38,44,45]. Dizziness and vertigo may also preclude subjects from immersion in virtual reality environments, since they are associated with vestibular disturbances, and disorders of balance.

2.4.6 Medication

Anti-motion sickness drugs such as hycosine can be effective in reducing symptoms of nausea during immersion in a virtual reality environment [19]. Hycosine hydrobromide was

administered to nineteen subjects forty minutes before a twenty minute exposure to an immersive virtual reality environment. A placebo compound was administered to another twenty subjects. Twenty five percent of the subjects in the placebo group reported nausea during the immersion and a ten minute post-immersion period, compared to only five percent of the subjects in the hycosine group. The results also showed that hycosine significantly reduced reports of other symptoms such as stomach awareness, headaches, eyestrain and disorientation. This was attributed to the central sedative action of the drug. It was suggested that hycosine offers a more rapid method of reducing side effects of virtual reality than adaptation. However some caution is necessary in the use of such drugs since they also have undesirable side-effects such as drowsiness, blurred vision and degraded cognitive and motor performance [46]. They may also inhibit adaptation to the virtual environment.

2.5 Experience of user

2.5.1 Previous exposure to the virtual reality system

Exposure durations of less than 10 minutes to some immersive virtual reality environments have been shown to result in significant incidences of nausea, disorientation and ocular problems [18]. The severity of motion-induced sickness symptoms has been shown to increase with increases in the duration of exposure to provocative motions during travel for durations up to at least 6 hours [42]. Kennedy *et al* [14] reported that longer exposures to simulated flight increased the intensity and duration of post-exposure postural disruptions. However, the incidences of nausea and postural problems have been shown to reduce with increased prior experience in both simulators [47] and in immersive virtual reality environments [19].

On initial exposure to a novel environment, symptoms of motion sickness will persist until an individual has adapted to any unusual visual-vestibular relationships. The strength of the initial symptoms and the rate of adaptation depend on factors such as age, gender and perceptual characteristics. On leaving the novel environment, symptoms may return until the individual has re-adapted to more normal visual-vestibular relationships. During repeated exposures to the same environment most subjects build up a degree of protective adaptation, which is retained for relatively long periods of time. However, studies have shown that there is no systematic relationship between an individual's initial rate of adaptation to a novel environment and the subsequent degree of protection.

Kennedy *et al* [13] have suggested that adaptation should not be relied upon to provide the solution to the problem of sickness in training applications. Subjects may adopt unusual strategies to avoid symptoms which are inappropriate or lead to degraded performance in real tasks.

2.5.2 Motion sickness history

An individual who has previously suffered from motion sickness in any motion environment is more likely to become sick in another provocative environment than a person with no history of motion sickness. Motion sickness history questionnaires [25] have been shown to have a significant predictive value for motion sickness susceptibility during flight simulation [31] and during exposure to a rotating visual surround [48].

There are some problems with the use of motion sickness histories to predict susceptibility in the general population due to differences in individual exposures to provocative situations. Nevertheless, a questionnaire should be able to identify individuals who are particularly susceptible, and with whom special precautions may need to be taken during initial exposures to immersive virtual reality environments.

2.5.3 Perceptual factors and personality

Reason and Graybiel [49] have suggested that motion sickness susceptibility is related to two perceptual factors: adaptability and receptivity. Adaptability refers to the rate at which an individual typically adjusts to conditions of sensory rearrangement. There is a wide and consistent variation in the rate at which normal individuals adjust to novel environments. Slow adaptors are said to report a more extensive history of motion sickness than fast adaptors. About 5% of individuals who are susceptible to motion sickness fail to adapt at all.

Receptivity refers to the intensity with which subjects respond to increasing stimulus magnitudes. Individuals reporting an extensive history of motion sickness tend to be more “receptive” to a given level of stimulus energy, irrespective of sensory modality. One study indicated that susceptible individuals tend to have a more emotional or autonomic response to both mental and physical stressors [50]. Positive and significant correlations have also been reported between neuroticism, as measured by the Eysenck Personality Inventory, and motion sickness susceptibility [50,51]. These findings may have particular implications for the exposure of patients with behavioural disorders.

2.6 Characteristics of the display

2.6.1 Luminance and contrast

Poor luminance and contrast have been identified as contributory factors to ocular side-effects caused by head-mounted displays. These are likely to interact with prismatic effects and interpupillary setting to increase susceptibility to ocular symptoms.

2.6.2 Resolution and frame rate

Low spatial resolution and low frame rates can lead to problems of temporal aliasing, similarly to low update rates (see Section 2.7) [52].

2.6.3 Flicker

Flicker in the display has been cited as a contributor to simulator sickness [38, 40]. It has also been suggested that flicker contributes to eye fatigue [40]. The point at which flicker becomes visually perceptible (i.e. the flicker fusion frequency threshold) is dependent on the refresh rate, luminance and field-of-view. As the level of luminance increases, the refresh rate must also increase to prevent flicker. The peripheral visual system is more sensitive to flicker than the fovea, so increasing the field of view increases the probability that an observer will perceive flicker. There is a wide range of sensitivities to flicker between individuals, and also a daily variation within individuals [53].

2.6.4 Inter-ocular distance

In a study of side-effects of immersion in a virtual reality environment, subjects who reported ocular symptoms were generally found to have the smallest inter-pupillary distances relative to the inter-ocular distance of the head-mounted display [54]. In another study, there were changes in ocular function in more than 50% of subjects following a ten-minute immersion in a virtual reality environment displayed on a head-mounted display with a fixed inter-ocular distance [21]. However, no significant changes in ocular function were found after immersions between 5 and 30 minutes in another virtual environment when the inter-ocular distance of the display was individually adjusted for each subject [37].

Mismatch between the inter-ocular distance of a bi-ocular head-mounted display and the inter-pupillary distance of the user will result in increased eyestrain due to disruptions in accommodation, convergence and binocular fusion. Low-cost head-mounted displays with no adjustment for inter-pupillary distance should be avoided for clinical applications. Care should be taken to accurately calibrate the inter-ocular distance of the display to the inter-pupillary distance of the user. This is especially important for a binocular display which is used to display stereo images.

2.7 System lags

The authors are not aware of any systematic studies of the effects of different system lags on the side-effects of simulators and virtual reality systems. One problem of designing such studies is that in all practical systems involving real-time interaction with a virtual environment there will be some lag between a user's actions and the displayed consequences. It is therefore difficult to establish baseline conditions. It is also difficult to measure and quantify system lags. The lag in a practical system cannot be represented by a simple time delay. All of the system components (position sensors, image processors and displays) have different temporal characteristics, some of which may be complex (e.g. combinations of time delays, sample-and-hold effects, quantisation introduced by low spatial resolution and low-pass filtering). A pure time delay may be expected to have different perceptual consequences than the delay due to update rate, which is characterised by a sample-and-hold phenomenon.

Different lags may be associated with different aspects of the simulation. An immersive virtual reality application may involve moving virtual objects within the environment, as a consequence of limb or control movements, as well as movements of the visual scene as a consequence of head position. Lags will be present in the orientation of the visual scene (between the sensing of head position and the display of an appropriately orientated visual scene) and in control actions (between the sensing of control or limb position and the display of the visual image).

Visual lags may have a greater capacity to induce visual-vestibular distortions than control lags. An exception to this may be a vehicle simulator, where the control action also affects the orientation of the user in virtual space. Visual lags result in errors in position and velocity between the head and the visual scene. The magnitudes of the position and velocity errors are proportional to the total time delay and to the velocity and acceleration of the head position sensor [55].

The most comprehensive study to date of side-effects in virtual reality environments employed a system with a reported total lag of about 0.3 seconds, although it is not clear if

this refers to a constant time delay, an update rate or a combination of effects [18,19]. The field-of-view of the LCD head-mounted display was 110° by 60°, with a comparatively low resolution of 360x240 pixels. A series of experiments were performed in which subjects moved through a series of virtual rooms using a 3D mouse control and interacted with different objects in the rooms (e.g. by picking them up and moving them). Over sixty percent of the subjects reported at least one symptom of simulator sickness during a twenty-minute immersion or a ten-minute recovery period. Of these subjects, almost half reported symptoms of nausea. In another study, three out of twenty subjects reported symptoms of nausea after a ten-minute immersion in an interactive virtual environment with a reported visual delay of 0.06 seconds and an update rate between 12 and 25 Hz [21]. System lags are generally assumed to be a major source of spatio-temporal distortions leading to sensory rearrangements.

However, the absence of data from identical virtual environments with different lag conditions makes it impossible to quantify the extent to which symptoms are affected by the lags or by their interactions with other parameters.

The update rate (i.e. the maximum rate at which new visual scenes are presented to the user) may be an important source of perceptual distortions [56]. Low update rates introduce a sample-and-hold effect, making objects appear to move in discrete spatial jumps. The visual system thus has to bridge the gaps between perceived positions by using spatio-temporal filtering [52]. Low frame rates (particularly when combined with high head velocities) may cause the coherence of the image motion to be lost, and several perceptual distortions may occur, including the appearance of reversals in the perceived motion direction, motion appearing jerky, and multiple images trailing behind the target. This phenomenon is referred to as temporal aliasing. Edgar and Bex [52] have discussed methods for optimising displays with low update rates so as to minimise this problem.

2.8 Movement through the virtual environment

2.8.1 Control of movements

In simulators, subjects have been shown to be less susceptible to motion sickness when they have control over the simulated motions [40,57]. There is a high incidence of motion sickness symptoms in subjects passively viewing a rotating visual surround with vertical stripes. When subjects walk on a circular treadmill in the opposite direction to the rotation no symptoms are reported during exposures of up to 15 minutes. This remains true even when the visual surround moves twice as fast as the treadmill. However, postural stability is disturbed when the surround is accelerated or decelerated, causing subjects to fall backwards or to lurch forwards. This postural disturbances would not be expected to occur if the speed of the surround was controlled by the speed of walking, since the changes in the visual stimulus would be consistent with the subject's previous experience [58].

The method of movement through a virtual environment may affect the level of side-effects. Several studies of side-effects in immersive virtual environments [17-19] have used a 3D mouse to generate movement. Regan and Price [59] have suggested that this device has the potential to generate conflict between visual, vestibular and somatosensory senses of body movement. It has been suggested that a more natural movement might be provided by coupling movement through a virtual environment to walking on a treadmill.

2.8.2 Speed of movement

The speed of movement through a virtual environment determines global visual flow (i.e. the rate at which objects flow through the visual scene). The rate of visual flow influencesvection and has been shown to be related to the incidence of simulator sickness [45]. Other motion conditions that have been observed to exacerbate sickness in simulators include tasks involving high rates of linear or rotational acceleration, unusual manoeuvres such as flying backwards and freezing or resetting the simulation during exposures [45].

2.9 Characteristics of the visual image

Simulators with wide field-of-view displays tend to have greater incidences of simulator sickness [13,40]. The field-of-view influences subjects' experiences ofvection due to moving visual scenes, which may be a primary cause of motion sickness in virtual environments [29]. Stern *et al* [60] have shown that restricting the width of the visual field to 15 degrees significantly reduces both circularvection and the symptoms of motion sickness induced by a rotating surround with vertical stripes (this device is called an optokinetic drum). Circularvection and motion sickness are also reduced by fixation on a central point in the visual field [60].

The total area of the display may be as important as the extent of peripheral stimulation. Anderson and Braunstein [61] have shown that peripheral stimulation is not always necessary to promote a strong sense of linearvection. They showed that linearvection could be induced by a moving display of radially expanding dots with a visual angle as small as 7.5° in the central visual field. They suggested that the type of motion and the texture in the display may be as important as the field-of-view in inducingvection.

2.10 Interaction with the task

2.10.1 Head movements

Head movements in simulators have been reported to be very provocative [40,57]. However Regan and Price [59] found that over a ten minute period of immersion in a virtual environment, there was no significant effect of type of head movement on reported symptoms. Sickness incidence was compared between two ten-minute exposures to an immersive virtual reality environment. One exposure required pronounced head movements and a rapid interaction with the system. During the other exposure, subjects were able to control their head movements and their speed of interaction to suit themselves. There was some evidence that the pronounced head movements initially caused higher levels of symptoms, but that subjects adapted to the conditions by the end of the exposures. No measurements were made of head movements, so the effects of the instructions given to the subjects on the velocity and duration of head movements is unclear. The total system lag was reported to be 300 ms, so even slow head movements may have resulted in significant spatio-temporal distortions [55].

Further systematic research is necessary to precisely determine the interaction between system lags and head movement velocity on the incidence of side-effects. Both the lags and

the head movements in such studies need to be quantified and strictly controlled. In the absence of more precise information, it would be prudent to restrict the magnitude and speed of head movements during an individual's initial immersion in a virtual environment.

2.10.2 Posture

The frequency of symptoms reported by seated subjects after immersion in a virtual reality environment has been reported to be slightly higher than the frequency of symptoms reported by standing subjects [59]. However, the differences were not statistically significant after ten minute immersions.

3. Interaction, Performance and Presence Within Virtual Reality Environments

The achievement of certain task performance criteria may be the primary objective of some applications. For instance, virtual environments designed for surgical training must realistically represent the real task that is being simulated. An important aspect of these simulations can be the measurement of performance so as to assess likely competence at the real task. The introduction of artefacts by the virtual environment which affect the performance of the task are likely to reduce the effectiveness of the training or lead to negative transfer of training to the real environment.

There have been many investigations of visual-motor co-ordination tasks in virtual reality systems and simulators. Most of these studies have focused on the effects of lags between the sensing of head, limb or control position and the movements of images on the display. Lags of a similar order to those present in many practical systems have been shown to have a significant effect on the performance of tracking, manipulation and reading tasks. Other studies have demonstrated benefits of stereoscopic displays to provide depth cues to aid the manipulation of virtual objects in three dimensions, such as is required in surgical simulation.

The essence of virtual reality is the ability to interact with a three-dimensional computer-generated environment. Some clinical applications may simply require subjects to be present within an interactive virtual environment. For example, applications are being developed for desensitisation of subjects to anxiety-provoking situations. The effectiveness of these applications is likely to be strongly dependent on the sense of presence within the virtual environment that is felt by the subjects.

There has been little systematic research to determine the effects of characteristics of the system or the task on an individual's sense of presence. Welch *et al* [62] have suggested that maximal presence will occur when the user:

- feels immersed within the virtual environment;
- feels capable of moving about in the virtual environment;
- has an intense interest in the interactive task.

Presence and performance are likely to interact. Some clinical applications require subjects to perform tasks which do not demand accurate visual-motor co-ordination. Even if performance is not affected by factors such as lags, the spatio-temporal distortions which are introduced into a user's interactions with the virtual environment have the potential to weaken the illusion of realism and of being present within a virtual world.

Table 3 shows factors associated with the system and the task which have been shown to affect either performance or the user's sense of presence within a virtual environment. The influence of these factors is discussed in the following sub-sections.

Table 3. Factors shown to influence presence and performance within virtual reality environments.

Factors affecting presence	Factors affecting task performance
<ul style="list-style-type: none">• feedback delays (system lags)• interactivity• pictorial realism	<ul style="list-style-type: none">• feedback delays (system lags)• update rate• monoscopic versus stereoscopic viewing

3.1 Factors affecting presence

3.1.1 Feedback delays and pictorial realism

It has been suggested that overall system lags of less than 0.3 seconds are necessary to maintain the illusion of immersion in a virtual reality environment, since with longer lags subjects start to dissociate their movements from the associated image motions [63,64]. It is unclear whether the authors attributed these effects to pure lags or the system update rates.

Pausch *et al* [40] have cited data from Westra and Lintern [65] to show that control lags may affect subjective impressions of a simulator more than they affect performance. Simulated helicopter landings were compared in simulators with system lags of 0.11 seconds and 0.22 seconds. The lags had only small effects on objective performance measures, but pilots believed that the lag had a larger effect than was indicated by the performance measures.

Welch *et al* [62] investigated the effects of a control lag and of pictorial realism on subjects' sense of presence in an immersive virtual reality driving simulation. The virtual environment was displayed on a stereoscopic head-mounted display with a horizontal field-of-view of 62.5°. Subjects rated their relative "feeling of being physically located in and surrounded by the portrayed visual world rather than in the laboratory" during paired comparison presentations of conditions. An increase from 0.2 seconds to 1.5 seconds in visual feedback of vehicle motions was found to significantly reduce the subjects' strength of presence. The effect of pictorial realism, which was represented by increased detail in the virtual environment, was found to have a significant but smaller effect on the strength of presence than the increased delay.

3.1.2 Interactivity and pictorial realism

In a similar experiment to their investigation of the effects of control lag, Welch *et al* [62] studied the effect of observer interactivity and of pictorial realism on subjects' sense of presence in an immersive driving simulation. Subjects either controlled the speed and direction of the simulated car using the steering wheel and pedals, or sat passively while the car "drove itself". The results indicated that interactivity was more important than pictorial realism for producing a strong sense of presence.

3.2 *Factors affecting performance*

3.2.1 *Feedback delays*

Experimental studies have investigated the effects of lags on the performance of tasks in different head-coupled systems. With target capture and tracking tasks using a head-slaved reticle, capture times and tracking errors were significantly increased by the imposition of a time delay of less than 0.1 seconds in the feedback of head position [66,67]. The delays were imposed on a minimum system lag of 0.04 seconds.

Time delays of 0.1 seconds or more have been shown to degrade performance of a simulated tele-operated tracking task and a pick-and-place task, which were both controlled by a pair of joysticks [68-70]. The tracking task involved keeping a ball inside a box, which moved along an unpredictable three-dimensional trajectory. The pick-and-place task involved placing four balls into appropriately sized boxes. There was an approximately linear increase with increasing delay in both tracking error and pick-and-place completion time. The tasks in these experiments were viewed on a space-stabilised head-mounted display and the lags affected both the visual display and the control task. In these experiments the limited field of view of the head-mounted display (22°) constrained subjects to turn their heads to keep the task in view on the display. The subjects increasingly inhibited their head movements as the system delay was increased because of the de-coupling between head position and the position of the displayed image.

The results of these experiments show that the performance of tasks involving fine visual-motor co-ordination in virtual reality environments can be expected to be degraded by visual lags and control lags as small as 0.1 seconds. Lags in immersive virtual reality systems with space-stabilised displays induce errors in the positions of visual images which are proportional to the velocities of head movements [55]. As the system lag increases, users will increasingly adopt unrealistic strategies which minimise head movements.

3.2.2 *Update rate*

Liu *et al* [69,70] investigated the effect of display update rates, in the range 0.1 to 100 frames per second, on the simulated tele-operated manual control task described in the previous section. With three inexperienced subjects, the root-mean-square tracking error was significantly increased by update rates below 10 frames per second. However, two experienced subjects were able to maintain performance of the tracking task with update rates as slow as 2 frames per second, suggesting that more experienced subjects are better able to cope with degraded conditions.

Richard *et al* [56] investigated the effect of display update rates between 1 and 28 frames per second on the manipulation of virtual objects using a data glove. The task was displayed either monoscopically on a cathode ray tube (CRT) display monitor, or stereoscopically on a liquid crystal display (LCD) head-mounted display. The task was not immersive, since the position and orientation of the images were not adjusted according to head position. The task involved tracking and grabbing a target ball, which moved in three dimensions within a virtual room. There were no significant differences in task completion times for frame rates between 14 and 28 frames per second on either display. With lower update rates the capture times were initially high, but decreased with the subjects' experience. The authors suggested that, since the conditions with higher frame rates were

closer to natural conditions, there was less need for the subjects to adapt to the task. With frame rates of 14 and 28 frames per second the subjects moved their hands continuously in space, but with frame rates less than 7 frames per second their tracking movements became saccadic (i.e. in discrete spatial jumps).

High update rates are necessary in virtual reality applications for the simulation of tasks which require high precision visual-motor co-ordination so as to avoid the adoption of unnatural movement strategies which could affect the transfer of training.

3.2.3 Stereoscopic versus monoscopic viewing

In the experiment described in the previous section to investigate the effect of display update rates on the manipulation of virtual objects, the difference in capture times between the first and the last trial was smaller with the stereoscopic display, particularly with the lower frame rates. Stereoscopic viewing provides more normal depth cues when manipulating virtual objects in three-dimensional space, and reduces the need to develop special strategies to compensate for unnatural conditions.

4. Human Factors Considerations for the Implementation of Clinical Virtual Reality Applications

In order to maximise the performance of virtual reality applications for their intended application, careful consideration needs to be made of the possible effects of the characteristics of the system and the task on the performance of users and on the incidence of possible side-effects. The discussions in Section 2 and Section 3 suggest some specific design recommendations, which are outlined in Section 4.2.

The users of virtual reality applications designed for clinical assessment and rehabilitation may have conditions which increase their susceptibility to known, or unanticipated, side-effects. Many of the reported effects of task and system characteristics on performance and well-being have been ascribed to distortions in the normal relationships between movements of the users, and the visual feedback of those movements. These distortions arise because of limitations in the spatial and temporal performance of virtual reality systems, or because image motions are presented which give the illusion of body motion in the absence of real motion. Some clinical applications of virtual reality may deliberately create further distortions in order to augment the stimulation and feedback provided by the visual images [11].

Special precautions need to be taken to ensure the safety and well-being of patients in virtual environments designed for either assessment or rehabilitation. These precautions should include consideration in the design of applications of factors which are known to influence the incidence side-effects of immersion in virtual environments, with special regard to the characteristics of the potential users (see Section 4.2). They should also include the implementation of procedures for managing the exposures of patients to the virtual reality environment. Suggestions for precautions which should be included in exposure management protocols are given in Section 4.1.

4.1 Managing exposures of patients to clinical virtual reality environments

Exposure management protocols for patients in virtual environments should include:

- screening procedures to detect individuals who may present particular risks;
- procedures for managing exposures to a virtual reality application so as to ensure rapid adaptation with minimum of symptoms;
- procedures for monitoring exposures for unexpected side-effects and to make sure the system meets its design objectives.

4.1.1 Screening procedures

The following information should be considered before exposing patients to virtual reality.

- (a) General state of health: patients should not be exposed if they are suffering from illnesses such as flu or ear infections, or from the effects of alcohol.
- (b) Medication: any drugs that patients are taking should be reviewed for possible effects on visual or vestibular function.
- (c) History of balance disorders: to determine whether special precautions may need to be taken to prevent falling during or after exposures to moving visual scenes.
- (d) History of motion sickness (see Reason and Brand [25]): to identify individuals who may have a high risk of developing simulator sickness symptoms.
- (e) Tests of ocular function should be considered to detect defects which could be exacerbated by head-mounted displays.

4.1.2 Management of exposures

The following factors merit consideration when managing a patient's exposures to a virtual reality environment.

- (a) Patients should be informed of the possible adverse effects of exposure to virtual reality environments before they are exposed. They should be encouraged to report symptoms as soon as they occur. They should also be warned about the possible delayed onset of symptoms.
- (b) Precautions should be taken to ensure that young, disabled or unsteady individuals, who may be at risk from falling, are provided with adequate support.
- (c) Durations of exposures to immersive or partially immersive virtual reality environments should be limited at first (an initial exposure limit of about 5 minutes may be appropriate). The durations of subsequent exposures may be gradually increased as the subject adapts to the sensory arrangements in the virtual environment. Patients should be monitored during the adaptation process for any side-effects, and exposures should be terminated when any symptoms become evident.
- (d) A time should be allowed for recovery after exposure to partially immersive or immersive virtual reality environments before engaging in potentially hazardous activities such as driving a car. Individuals experiencing postural disturbances or ocular symptoms should be monitored until symptoms have dissipated. In this case, potentially hazardous activities such as driving should be restricted for 12 to 24 hours.
- (e) All patients should be continuously supervised during exposures to virtual reality.
- (f) There should be an adequate procedure for adjusting head-mounted displays for individual users. Special attention should be paid to optical factors such as inter-pupillary distance.

- (g) Post-exposure checks of ocular function should be considered to detect any long-term problems, especially in applications using head-mounted displays.

4.1.3 System monitoring

The incidence of any side effects in a particular system, and the exposure times up to the appearance of symptoms, should be routinely logged. The incidence rates for different categories of symptoms should be regularly reviewed. This will provide an assessment of potential problem areas and allow early application of appropriate counter-measures.

4.2 Recommendations for the design of applications

4.2.1 System lags and update rates

The system should minimise the total delay between head position sensing and the presentation of an appropriate image. This may involve the selection of suitable position sensors [71,72] and the minimisation of synchronisation errors [63]. If the total delay cannot be reduced below 0.1 seconds then consideration should be given to implementing a predictive algorithm for head position in order to reduce the effects of the lag [63]. Similarly, the system update rates should be maximised.

Minimising the visual delay and maximising update rates should reduce both the probability of simulator sickness symptoms, and also minimise the interference with the user's interactivity with the environment, and the performance of tasks. This is especially important where the effectiveness of the application depends on the performance of a visual-motor task. Significant delays and low update rates may result in users adopting unnatural movement strategies which could interfere with the transfer of training to a real task.

While the minimisation of spatial and temporal distortions between the motions of sensors and displays is the normal design requirement, it is recognised that clinical applications may sometimes require particular distortions to be imposed on image movements. In this case the possible side-effects of those manipulations should be considered.

4.2.2 Head movements

The application should be designed to require the minimum of head movements. This is particularly important during initial exposures, before the user has acquired any adaptation to the novel sensory environment.

4.2.3 Interaction with the virtual environment

The maximum speed of self-movement through an immersive virtual environment should be limited to a very slow rate if it is not under the control of the user. Where possible, movement should be initiated by a natural means, such as walking. Unusual and extraordinary manoeuvres, such as abruptly freezing image movements or resetting the view, should be avoided.

4.2.4 Motions of visual scenes

In applications in which wide field-of-view moving scenes are presented in the absence of body motions it may be necessary to restrict the durations of initial exposures, to enable the user to adapt to the visual conditions. Moving images sensed by peripheral vision, in the absence of corresponding vestibular or somatosensory information, can induce a strong sense of vection and can be highly nauseogenic. Vection may also induce inappropriate postural re-adjustments, so supports such as hand rails or harnesses should be provided for standing individuals. This is particularly important if the application will be used with young, disabled or unsteady individuals.

4.2.5 Display characteristics

When choosing a head-mounted display it is important to consider the potential effects of the optical design on ocular problems. Low-cost head-mounted displays with no adjustment for inter-pupillary distance should be avoided for clinical applications. This is especially important for a binocular display which is used to display stereo images.

5. Directions for Future Research

Few systematic studies have been carried out to determine the effects of the characteristics of virtual reality systems on symptoms of sickness and other problems experienced by users. Hence, much of the evidence for the influence of these factors has to be inferred from studies of visually-induced motion sickness and transport-induced motion sickness (i.e. sickness caused by vehicle motions), as well as the effects of exposures to simulators. There is a need for more systematic fundamental research on virtual reality systems so as to improve understanding of the interaction between the factors listed in Section 2 and Section 3 in the causation of side-effects, and in influencing the effectiveness of virtual environments for simulation and training.

Many of the undesirable side-effects of exposures to immersive virtual reality can be attributed to distortions of the spatial and temporal relationships between body movements and corresponding movements of the visual scene. An important source of such distortions is the time delay between the measurement of head position and the display of an appropriately orientated visual image. However there have been no systematic studies of the effects of different lag conditions on the incidence of side-effects. The distortions introduced by system lags are also affected by the frequencies and magnitudes of the user's head motions, as well as the content of the visual scene. In order to be able to improve understanding of the likely effects of system characteristics on the incidence of adverse side effects studies are needed in which the above variables are quantified and varied in a controlled manner.

6. General Conclusions and Recommendations

The use of virtual reality has many potential benefits for medical training and for clinical assessment and rehabilitation. In order to ensure that these benefits are realised it is

necessary to understand the factors which could affect the safety, well-being and performance of potential users. There are well-documented side-effects of exposures to virtual reality environments which could lead to problems including:

- symptoms of motion sickness;
- strain on the ocular system;
- degraded limb and postural control;
- reduced sense of presence;
- the development of responses inappropriate for the real-world which might lead to negative training.

This chapter reviews current knowledge concerning some of the factors which are likely to influence adverse effects of virtual reality environments, and which need to be considered in the design of applications. The introduction of patients to virtual reality environments, for assessment, therapy or rehabilitation, introduces particular safety and ethical issues. Patients exposed to virtual reality environments for assessment and rehabilitation may have disabilities which increase their susceptibility to side-effects. Precautions should be taken to ensure the safety and well-being of patients, including the establishment of protocols for monitoring and controlling exposures of patients to virtual reality environments. Issues have been identified which need to be considered when formulating such protocols.

Many of the adverse side-effects of virtual reality environments can be attributed to time delays and other spatial and temporal distortions due to limitations in hardware and software. There remains a need for fundamental and systematic research so as to improve understanding of the influence of the spatio-temporal characteristics of virtual reality systems on both normal users and those with disabilities.

7. References

- [1] J. Wann and M. Mon-Williams, What does virtual reality NEED?: human factors issues in the design of three-dimensional computer environments, *International Journal of Human-Computer Studies* 44 (1996) 829-847.
- [2] D. Ota, L. Bowen, T. Saito, R. Lea and J. Keller, Virtual reality in surgical education, *Computers in Biology and Medicine* 25 (1995) 127-137.
- [3] A. Dumay and G. Jense, Endoscopic surgery simulation in a virtual environment, *Computers in Biology and Medicine* 25 (1995) 139-148.
- [4] C. Von Pichler, K. Radermacher, W. Boeckmann, G. Rau and G. Jakse, Stereoscopic visualisation in endoscopic surgery: problems benefits and potentials, *Presence* 6 (1997) 198-217.
- [5] I. Hunter, L. Jones, M. Sagar, S. Lafontaine and P. Hunter, Ophthalmic microsurgical robot and associated environment, *Computers in Biology and Medicine* 25 (1995) 173-182.
- [6] M. North, S. North and J. Coble, Effectiveness of virtual environment desensitization in the treatment of agoraphobia, *Presence* 5 (1996) 346-352.
- [7] B. Rothbaum, L. Hodges, R. Kooper, D. Opdyke, J. Wilford and M. North, Effectiveness of computer-generated (virtual reality) graded exposure in the treatment of acrophobia, *American Journal of Psychiatry* 152 (1995) 626-628.
- [8] G. Riva, The virtual environment for body image modification (VEBIM): development and preliminary investigation, *Presence* 6 (1997) 106-117.
- [9] F. Rose, E. Attree and D. Johnson, Virtual reality: an assistive technology in neurological rehabilitation, *Current Opinion in Neurology* 9 (1996) 461-467.
- [10] D. Strickland, A virtual reality application with autistic children, *Presence* 5 (1996) 319-329.
- [11] T. Kuhlen and C. Dohle, Virtual Reality for physically disabled people, *Computers in Biology and Medicine*, 25 (1995) 205-211.
- [12] L. Whalley, Ethical issues in the application of virtual reality to medicine, *Computers in Biology and Medicine*, 25 (1995) 107-114.

- [13] R. Kennedy, N. Lane, K. Berbaum and M. Lilienthal, Simulator sickness in US Navy flight simulators, *Aviation, Space and Environmental Medicine* 60 (1989) 10-16.
- [14] R. Kennedy, J. Fowlkes, K. Berbaum and M. Lilienthal, Use of a motion sickness questionnaire for prediction of simulator sickness, *Aviation, Space and Environmental Medicine* 63 (1992) 588-593.
- [15] R. Kennedy, J. Fowlkes and M. Lilienthal, Postural and performance changes following exposures to flight simulators, *Aviation, Space and Environmental Medicine* 64 (1993) 912-920.
- [16] R. Kennedy, D. Lanham, J. Drexler, C. Massey and M. Lilienthal, Cybersickness in several flight simulators and VR devices: a comparison of incidences, symptom profiles, measurement techniques and suggestions for research. In: Proc. FIVE'95 (Framework for Immersive Virtual Environments), University of London, December 1995.
- [17] S. Cobb, S. Nichols and J. Wilson, Health and safety implications of virtual reality: in search of an experimental methodology. In: Proc. FIVE'95 (Framework for Immersive Virtual Environments), University of London, December 1995.
- [18] E. Regan and K. Price, The frequency of occurrence and severity of side-effects of immersion virtual reality, *Aviation, Space and Environmental Medicine* 65 (1994) 527-530.
- [19] E. Regan, An investigation into nausea and other side-effects of head-coupled immersive virtual reality, *Virtual Reality* 1 (1995) 17-32.
- [20] R. So, An investigation of the effects of lags on motion sickness with a head-coupled visual display. In: Proceedings of the U.K. Informal Group Meeting on Human Response to Vibration, Institute of Naval Medicine, Alverstoke, U.K., 1994.
- [21] M. Mon-Williams, J. Wann and S. Rushton, Binocular vision in a virtual world: visual deficits following the wearing of a head-mounted display, *Ophthalmic and Physiological Optics*, 13 (1993) 387-391.
- [22] R. Kennedy, N. Lane, M. Lilienthal, K. Berbaum and L. Hettinger, Profile analysis of simulator sickness symptoms: application to virtual environment systems, *Presence* 1 (1992) 295-301.
- [23] D. Baltzley, R. Kennedy, K. Berbaum, M. Lilienthal and D. Gower, The time course of postflight simulator sickness symptoms, *Aviation, Space and Environmental Medicine* 60 (1989) 1043-1048.
- [24] T. Unga, Simulator-induced syndrome: evidence for long-term aftereffects, *Aviation, Space and Environmental Medicine* 60 (1989) 252-255.
- [25] J. Reason and J. Brand, *Motion sickness*. Academic Press, London, 1975.
- [26] I. Howard, The perception of posture, self-motion and the visual vertical. In: K. Boff, L. Kaufman and J. Thomas (eds.), *Handbook of Human Perception and Performance*, Vol. 1, Sensory Processes and Perception. Wiley, New York, 1986.
- [27] G. Zacharias and L. Young, Influence of combined visual and vestibular cues on human perception and control of horizontal rotation, *Experimental Brain Research* 41 (1981) 159-171.
- [28] L. Young, J. Dichgans, R. Murphy, and T. Brandt, Interaction of optokinetic and vestibular stimuli in motion perception, *Acta Otolaryngologica*, 76 (1973) 24-31.
- [29] L. Hettinger and G. Riccio, Visually induced motion sickness in virtual environments. *Presence* 1 (1992) 306-310.
- [30] B. Cheung, I. Howard and K. Money, Visually-induced sickness in normal and bilaterally labyrinthine-defective subjects, *Aviation, Space and Environmental Medicine* 62 (1991) 527-531.
- [31] S. Hu, K. Glasser, S. Todd, M. Tamera, B. Stanton, and M. Gruber, Motion sickness susceptibility to optokinetic rotation correlates to past history of motion sickness. *Aviation, Space and Environmental Medicine*, 67 (1996) 320-324.
- [32] F. Lestienne, J. Soechting and A. Berthoz, Postural re-adjustments induced by linear motion of visual scenes, *Experimental Brain Research* 28 (1977) 363-384.
- [33] J. Lishman and D. Lee, The autonomy of visual kinaesthesia, *Perception* 2 (1973) 287-294.
- [34] J. Dichgans, K. Mauritz, J. Allum and T. Brandt, Postural sway in normals and atactic patients: analysis of the stabilising and destabilising effects of vision. *Aggressologie* 17c (1976) 15-24.
- [35] L. Nashner, Computerized Dynamic Posturography. In: G. Jacobson, C. Newman and J. Kartush (eds.), *Handbook of Balance Function Testing*. Mosby, St Louis, 1993.
- [36] Ebenholtz, Motion sickness and oculomotor systems in virtual environments, *Presence* 1 (1992) 302-305.
- [37] S. Rushton, M. Mon-Williams and J. Wann, Binocular vision in a bi-ocular world: new generation of head-mounted displays avoid causing visual deficit, *Displays* 15 (1994) 255-260.
- [38] J. Frank, R. Kennedy, R. Kellog and McCauley, Simulator sickness: a reaction to a transformed perceptual world I. scope of the problem. In: Proc. Second Symposium of Aviation Psychology, Ohio State University, Columbus OH, 25-28 April 1983.

GIUSEPPE RIVA (Ed.)

Virtual Reality in Neuro-Psycho-Physiology

1997, 1998 © Ios Press: Amsterdam, Netherlands.

- [39] E. Kolasinski, Simulator sickness in virtual environments. Technical Report 1027, U.S. Army Research Institute for the Behavioral and Social Sciences, Alexandria VA, 1995.
- [40] R. Pausch, T. Crea and M. Conway, A literature survey for virtual environments: military flight simulator visual systems and simulator sickness, *Presence* 1 (1992) 344-363.
- [41] M. Griffin, *Handbook of Human Vibration*. Academic Press, London, 1990.
- [42] A. Lawther and M. Griffin, The motion of a ship at sea and the consequent motion sickness amongst passengers, *Ergonomics* 29 (1986) 535-552.
- [43] R. Stern, S. Hu, R. LeBlanc and K. Koch, Chinese hyper-susceptibility to vection-induced motion sickness, *Aviation, Space and Environmental Medicine*, 64 (1993) 827-830.
- [44] R. Kennedy, M. Lillenthal, D. Baltzley, G. Allgood and D. Gower, Consistency across measures of simulator sickness: implications for a biocybernetic safety reporting device. In: *Proc. SAFE Association 25th Annual Symposium, Las Vegas, 16-19 November, 1987*, A89-1052-01-54, 95-100.
- [45] M. McCauley and T. Sharkey, Cybersickness: perception of self-motion in virtual environments, *Presence* 1 (1992) 311-318.
- [46] R. Kennedy, R. Odenheiner, D. Baltzley, W. Dunlap and C. Wood, Differential effects of scopolamine and amphetamine on micro-computer-based performance tests, *Aviation, Space and Environmental Medicine*, 61 (1990) 615-621.
- [47] J. Crowley, Simulator sickness: a problem for army aviation, *Aviation, Space and Environmental Medicine* 58 (1987) 355-357.
- [48] R. Kennedy, J. Fowlkes, K. Berbaum, M. Lillenthal, Predictive validity of a motion sickness questionnaire for simulator sickness. NTSC TR 87-011, Naval Training Systems Center, Orlando FL, 1987.
- [49] J. Reason and M. Graybiel, Factors contributing to motion sickness susceptibility: adaptability and receptivity. In: M. Lansberg (ed.), *Predictability of Motion Sickness in the Selection of Pilots*, AGARD Conference Proceedings No 109, 1972.
- [50] W. Collins and M. Lentz, Some psychological correlates of motion sickness susceptibility, *Aviation, Space and Environmental Medicine* 48 (1977) 587-594.
- [51] J. Wilding and R. Meddis, Personality correlates of motion sickness, *British Journal of Psychology* 63 (1972) 619-620.
- [52] G. Edgar and P. Bex, *Vision and Displays*, In: K. Carr and R. England (eds.), *Simulated and Virtual Realities - Elements of Perception*. Taylor and Francis, London, 1995.
- [53] K. Boff and J. Lincoln, *Engineering data compendium: perception and performance*. Armstrong Aerospace Medical Research Laboratory, Wright Patterson AFB, OH, 1988.
- [54] E. Regan and K. Price, Some side-effects of immersion virtual reality: an investigation into the relationship between inter-puillary distance and ocular related problems. Report no. 93R023, Army Personnel Research Establishment, Farnborough, U.K., 1993.
- [55] S. Bryson and S. Fisher, Defining, modeling and measuring system lag in virtual environments, *SPIE Stereoscopic Displays and Applications* 1256 (1990) 98-109.
- [56] P. Richard, G. Birbent, P. Coiffet, G. Burdea, D. Gomez and N. Langrana, Effect of frame rate and force feedback on virtual object manipulation, *Presence*, 5 (1996) 95-108.
- [57] J. Lackner, Human orientation, adaptation and movement control. In: *Motion Sickness, Visual Displays and Armored Vehicle Design*, Ballistic Research Laboratory, Washington DC, April 1990.
- [58] P. DiZio and J. Lackner, Spatial orientation, adaptation, and motion sickness in real and virtual environments, *Presence* 1 (1992) 319-328.
- [59] E. Regan and K. Price, Some side-effects of immersion virtual reality: the effects of increasing head movements, of rapid interaction, and of seated subjects. Report no. 93R022, Army Personnel Research Establishment, Farnborough, U.K., 1993.
- [60] R. Stern, S. Hu, R. Anderson, H. Leibowitz and K. Koch, The effects of fixation and restricted visual field on vection-induced motion sickness, *Aviation, Space and Environmental Medicine* 61 (1990) 712-715.
- [61] G. Andersen and M. Braunstein, Induced self-motion in central vision, *Journal of Experimental Psychology, Human Perception and Performance* 11 (1985) 122-132.
- [62] R. Welch, T. Blackmon, A. Liu, B. Mellers and L. Stark, The effects of pictorial realism, display of visual feedback, and observer interactivity on the subjective sense of presence, *Presence* 5 (1996) 263-273.
- [63] M. Wioka, Lag in multi-processor virtual reality, *Presence* 4 (1995) 50-63.
- [64] R. Held and N. Durlach, Telepresence, time delay and adaptation. In: S. Ellis (ed.), *Pictorial communication in virtual and real environments*. Taylor and Francis, New York, 1991.

GIUSEPPE RIVA (Ed.)

Virtual Reality in Neuro-Psycho-Physiology

1997, 1998 © Ios Press: Amsterdam, Netherlands.

- [65] D. Westra and G. Lintern, Simulator design features for helicopter landing on small ships. NAVTRASYSCEN 81-C-0105, Naval Training Systems Center, Washington DC, 1985.
 - [66] R. So and M. Griffin, Effects of lags on human-operator transfer functions with head-coupled systems. *Aviation, Space and Environmental Medicine* 66 (1995) 550-556.
 - [67] R. So and M. Griffin Head-coupled virtual environment with display lag. In: K. Carr and R. England (eds.), *Simulated and Virtual Realities - Elements of Perception*. Taylor and Francis, London, 1995.
 - [68] G. Tharp, A. Liu, L. French, S. Lai and L. Stark, Timing considerations of head-mounted display performance. *SPIE Human Vision, Visual Processing and Digital Display III* 1666 (1992) 570-576.
 - [69] A. Liu, G. Tharp, M. Hirose and L. Stark, Visual factors affecting human operator performance with a head-mounted display. *SAE Technical Paper* 911389, 1991.
 - [70] A. Liu, G. Tharp, L. French, S. Lai and L. Stark, Some of what one needs to know about using head-mounted displays to improve teleoperator performance, *IEEE Transactions on Robotics and Automation* 9 (1993) 638-648.
 - [71] K. Meyer, H. Applewhite and F. Biocca A survey of position trackers. *Presence* 1 (1992) 173-200.
 - [72] B. Adelstein, E. Johnston and S. Ellis, Dynamic response of electromagnetic spatial displacement trackers, *Presence* 5 (1996) 302-318.
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