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Health and safety implications of virtual reality: a review of empirical evidence

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Abstract

For the last 10 years a number of papers have been written that discuss human factors issues associated with virtual reality (VR). The nature of these papers has gradually evolved from speculation and anecdotal report to empirical research. Despite developments in VR technology, some participants still experience health and safety problems associated with VR use-termed VR-induced symptoms and effects (VRISE). The key concern from the literature is VR-induced sickness, experienced by a large proportion of VR participants, but for the majority these effects are mild and subside quickly. This paper makes a number of recommendations regarding the future direction of research into health and safety implications of VR, including the need to take into account the way in which VR is being used when conducting empirical research: first, to ensure that studies consider both effects and their consequences; second, to ensure that empirical trials reflect the actual likely context of VR use; third, to consider interactions between effects; and finally, to consider ways in which effects can be managed. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

For the last 10 years a number of papers have been written that discuss human factors issues associated with virtual reality (VR). The nature of these papers has gradually evolved from speculation and anecdotal report to descriptions of original empirical research. This paper reviews the current state of play in research into health and safety implications of VR,[1] and identifies the key issues that have been found to be of concern. Suggestions will be made as to the key research questions and appropriate research approaches that should be applied in continuation of this research.

It is worth noting the range of VR technology that has been developed and used in recent years. The initial focus of virtual environment (VE) research and development was on head-mounted display (HMD)-based systems. HMDs usually contain tracking systems that allow the change in the participant's head position to be reflected in an updated visual scene. These displays also usually have the potential to provide a stereoscopic display, where different, overlapping images are presented to each eye. However, more recently, technical development has moved more towards the use of large screen projection displays, that aim to physically enclose the user by including a curved display (such as in a reality theatre) or using multiple projection screens (e.g. CAVE). These may also use shutter glasses to provide stereoscopic viewing. Concurrently, particularly in the area of VR for education, work has continued on the development of desktop-based VEs. Whilst these VR set-ups do not physically enclose the user, they retain the potential to simulate environments that may psychologically involve the participant.

The scarcity of structured evaluations of the effects of VR until the past few years meant that reports by journalists in popular science journals made an initial impact on general knowledge of potential negative effects of VE use within the VR community. These are still likely to be the primary source of information about VR effects for the general public.

Early concerns focused on psychological and social implications of VR use as much as physical or physiological effects such as sickness. Issues highlighted included addiction (Arthur, 1992; Sherman, 1992); difficulties associated with "reentry" into the real world

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[1] Throughout this paper the term VR will be used generally to refer to the technology used to produce a virtual environment (VE)-the 'world' displayed by VR technology.

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after spending some time in the VE (Sherman, 1992); morality (Whitby, 1993) and participant self-esteem (Bennett, 1996). See Wilson, 1996 for reviews of these concerns.

However, whilst the articles considering psychological effects were mainly speculative, others presented anecdotal reports or experimental results from research labs. Tom Furness of the HIT Lab at the University of Washington in Seattle was quoted as saying:

> Cheap, poorly engineered products could leave users with long-term visual disturbances (Tom Furness, quoted in Seymour, 1996).

This was thought to be due to long-term adaptation of the vestibular ocular reflex (VOR)—implying that the brain had physically changed and formed new neural pathways to compensate for the disruption to the VOR that could later lead to "flashbacks" resulting from unpredictable switching between the original and changed neural pathways (Seymour, 1996).

A number of papers have attempted to identify the likely effects that may result from VR use. It is possible to classify the types of effects that have emerged according to a number of parameters, including whether they are direct or indirect, their time of onset or their underlying causative mechanism (e.g. physiological or psychological)—see Stanney et al., 1998; Nichols, 1999b. However, the process of effect categorisation can be a distraction from what should be the key determinant of what types of effects we should examine, and how we should examine them; that is, whether the consideration of the problems associated with VR use are "a significant issue—both for development of VR/VE and for its safe and effective use?" (Wilson, 1997).

Table 1 shows a list of the issues which it has been suggested may result from VE use. It is important to emphasise that this table may not be comprehensive, and that the effects listed are those that have been *suggested* rather than empirically identified. It should also be noted that the table includes effects that could be construed as being both "positive" and "negative", but although this categorisation has been used by the authors in the past (see Nichols, 1999b), it is now felt that this is not a useful distinction, due to the fact that one effect may be interpreted as either positive or negative depending on an individual, or the purpose for which the VE is being used. For example, an increase in heart rate could be an indication of increased arousal from and enjoyment of an experience of using VR, or it could be associated with the experience of VR-induced sickness, or a feeling of panic due to being physically restricted by wearing an HMD or being in a CAVE. Another example is from the use of VR for rehabilitation; whilst research into human factors issues associated with VR use has tended to focus on designing VEs and VR systems so that any long-term changes in physical behaviours or responses as a result of VR use are avoided by designing technology to be as intuitive and natural as possible, the use of VR in rehabilitation takes the opposite approach and *aims* to change the way in which people behave in the outside world after a period of VE use.

The goal of this review paper is to identify the VR/VE effects that have been examined in empirical work, and review the implications for future development, implementation and use of VR technology. The main focus of the paper is on the effects of VR-induced sickness, with reference to other associated effects such as postural instability. Other effects that have also been researched, but are not reported here, include physiological changes (see Ramsey, 1999) and presence (see Barfield et al., 1995; Witmer and Singer, 1998; Nichols et al., 2000a, b; Slater et al., 1994). In addition, the effects of display quality, dynamics, response/control design and feedback on usability and performance are not covered; for a review of usability issues associated with VR, see Neale, 2001.

2. Empirical evidence

Table 2 summarises the details of 35 previous studies performed to examine effects of VR use, to assess the impact of a number of different factors on a selection of effects.

It is apparent that the effect most frequently measured was VR-induced sickness, a phenomenon similar to simulator sickness and sometimes referred to as "cybersickness" which has been extensively discussed in the literature. VR-induced sickness is thought to occur as a result of conflicting input to the visual and vestibular senses, possibly explained by sensory conflict theory (see Reason and Brand, 1975). In VR one such conflict results from situations where movement is achieved via a hand-held input device. The visual system is presented with simulated movement, but the vestibular system registers a static position of the participant.

Kennedy and Fowlkes (1992) state that the prevalence of sickness symptoms in simulator users ranges from 20% in the "best" simulator to 60% in the "worst". It is also noted that after effects can persist for several hours, and it is these effects that may particularly present a safety risk. There are also two notable characteristics of simulator sickness. First, it is polysymptomatic, in that no one symptom predominates in all persons, thus making the examination of symptom groups such as nausea, oculomotor and disorientation, derived from the frequently applied Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993a, b) particularly appropriate. Second, it is polygenic, in that equipment, simulator usage and variables associated

Table 1
Suggested potential human factors issues resulting from VE use

Addiction	Biochemical change	Blurred vision
Cardiovascular change	Changes in motor performance	Changes in perceptual judgement
Enjoyment	Equipment fit	Eyestrain
Frustration	Gastrointestinal change	Hallucinations and visual flashbacks
Isolation	Musculoskeletal discomfort	Participant attitudes
Perceptual shifts and disorientation	Postural instability	Posture demands
Presence	Respiratory change	Stress and mood change
Transfer of training	Visual changes	VR-induced sickness

with participant characteristics may all have an influence on the type and severity of symptoms experienced.

> A given simulator may cause symptoms that fall into none, one or more of all the clusters, depending on the mechanism(s) by which the human is affected (Kennedy et al., 1992).

A number of differences between sickness symptoms experienced by simulator users and VR users have been observed. Stanney et al. (1997) describe the different profiles of VR-induced sickness compared to simulator sickness. They note that there is a higher overall level of symptoms for VR participants, but less predominance of oculomotor symptoms, with more nausea and disorientation being experienced.

Empirical data are available to determine the general prevalence of VR-induced sickness. In experiments conducted at the US Army Research Institute, early exits due to high symptom levels ranged from 4% to 16%, and 94% of those occurred within 10 min of immersion. VE sickness scores were on average higher than for simulators (Lampton et al., 1994a, b).

In two studies, Regan and Price (1993a, b) found 5–8% of participants withdrew before the end of the 20 min intended immersion time; 42% of the total sample in one study experienced sickness (Regan and Price, 1993a). Kolasinki (1996) also found evidence that 30% of the experimental sample experienced effects after VR immersion.

In a series of experiments for the Health and Safety Executive in the UK, Nichols et al. (2000a, b) examined VR-induced symptoms and effects (VRISE). These included under a number of conditions: in HMD, desktop, standard projection screen and reality theatre in normal viewing conditions; active desktop viewing under light vs. dark conditions; and active vs. passive control of movement of a VE viewed on a projection screen. In general, symptoms were more prevalent and severe as a result of participating in a HMD viewing condition compared with viewing VEs on desktop, standard projection screen or reality theatre displays. Lighting condition did not have an effect on VRISE, but being able to control movement within a VE reduced the level of reported symptoms. Overall, 70% of the total participant sample (221 participants) experienced an increase in symptoms from VE exposure. Generally these symptoms were mild and short-lived, subsiding within 10 min of exiting the VE. However, symptoms were more severe and long lasting (up to 8 h post-exposure) for participants who were diagnosed with classic migraine.

Therefore, across all studies it appears that a large proportion of the population report some increase in sickness symptoms after VE use. Although for the majority these symptoms are mild, and subside quickly, a small percentage of participants do experience sickness to an extent where they are unable to continue using VR. In order to make useful recommendations for those designing or using VR, it is necessary to isolate the effects of different influential factors. These factors can be categorised as being associated with the VR system (e.g. display type, tracking, resolution); VE design (e.g. number of colours, complexity, speed of object movement); circumstance of use (e.g. training, length of period of use, environmental conditions); and individual participant characteristics (e.g. age, gender, personality, motion sickness history). The following section of the paper considers the studies that have examined the impact of these factors in more detail.

3. Impact of influential factors

3.1. VR technology characteristics

Biocca (1992) suggested that the causes of VR-induced sickness could be a "technical problem" that would disappear as the technology developed. However, whilst technical developments have reduced initial problems such as lag between participant input of movement and display update, the conflict between visual and vestibular input remains. When considering other effects, such as physical ergonomics issues associated with HMD comfort, technical advances have reduced obvious problems such as excess HMD weight, but issues associated with ease of adjustability of HMDs remain. The influence of a number of specific technical variables has been investigated in empirical work.

The presence of head tracking has been suggested to contribute to symptoms. Whilst Ehrlich and Singer

Table 2
Summary of empirical data

	Authors	Experiment description	Effects measured	VR system and VE	Participants	Results
1	Allen and Singer (1997)	Effect of interactivity (high-treadmill vs. low-joystick), virtual terrain detail (distinctive vs. non-distinctive) and experience on direction and distance estimation	Landmark direction estimation accuracy	Silicon Graphics ONYX with Virtual Research VR4 HMD. Movement controlled by treadmill or 6DOF joystick	32 students (20 male, 12 female) from University of Central Florida	Some over-estimation of distance to near landmarks and under-estimation to far landmarks. Better accuracy found using joystick than treadmill
			Landmark distance estimation accuracy	VE = virtual terrain		
2	Bailey and Witmer, (1994)	(a)[a] Effectiveness of training route knowledge in VR vs. real world or symbolic rehearsal	(a) Route knowledge in actual building	(a) Fakespace BOOM2 control and display	(a) 60 participants	Higher level of interactive exposure resulted in better route knowledge
		(b) Effect of instructional technique (exploratory—following successive landmarks vs. restrictive—following left–right instructions) and head tracking (coupled vs. uncoupled) on route knowledge	Presence	Silicon Graphics CRIMSON	(b) 64 participants	Negative correlation between presence and sickness
			(b) Route knowledge	(b) Silicon Graphics CRIMSON		Positive correlation between presence and route knowledge performance
			Knowledge of building configuration Presence Sickness	Virtual Research Flight Helmet with standard joystick VE = virtual building		Negative correlation between sickness and route knowledge performance
3	Bauer et al. (1996)	Ergonomics quality of HMDs—comparison of three HMDs	Subjective fatigue	Forte Technologies VPX1	12 participants (7 male, 5 female) aged 14–57	No change in subjective fatigue, improvement in concentration (probably due to practice effect); Significant mean increase in fusion frequency
			Flicker fusion frequency	Virtual Research Flight Helmet		VFX1 most comfortable HMD—lower weight, more adaptable to individual head shape
			Comfort	*n*-vision Datavisor 10 × VEs = Virtual building, virtual landscape, virtual pyramid		
4	Calvert and Tan (1994)	Comparison of observing, playing and replication physical movements involved in VR game	Pulse rate	Virtuality system—Visette HMD with "gun" input device	36 participants (18 male, 18 female) middle class college students	VR participants increased more in pulse rate (arousal) than observers or movement only control condition. Also more dizzy/nauseated, and more aggressive thoughts
			Affective adjective checklist	VE = dactyl nightmare		
			Aggressive thoughts	Observation group—viewed another person's VR immersion on 3 ft × 3 ft video monitor		
			Sickness			

5	Cobb (1999)	Use of static, dynamic and posturographic postural stability techniques in measuring the effect of immersion in a VE	Postural stability (static and dynamic tests; tandem Romberg, sway magnetometry) Sickness	Virtuality Elysium using a HMD VE = "zone hunter" game consisting of tunnels and rooms	40 participants (28 male, 12 female) aged 18–26, students	Mild, short-lived postural instability only evident when measured using a post urographic technique under a normal stance static posture No correlation between self-reported symptoms and postural stability measures
6	Cobb and Nichols (1999)	Effect of VE immersion on postural stability	Postural stability (normal stance and tandem Romberg) Sickness	Virtuality Elysium system—Visette HMD VE = "zone hunter" game consisting of tunnels and rooms	40 participants (28 male, 12 female) aged 18–26, students	Sway magnetometry showed an increase in postural instability in normal stance post-immersion. Other measures were not sensitive to this change No correlation between self-reported symptoms and performance measures of postural instability
7	Eggleston et al. (1997)	Effect of FOV (three levels) and task difficulty (moderate vs. high) on movement task performance in VR vs. natural world	Movement time performance (tapping task)	Kaiser SIMEYE HMD tracked "tapping pencil" device VE = virtual tabletop and targets (w. real world table)	4 male participants	Effect of FOV differed with respect to task difficulty. For moderate difficulty worse performance on smaller FOV (possibly due to head movements required), no effects of FOV for high difficulty
8	Ehrlich and Singer (1996)	Effect of stereo vs. mono; head tracking vs. no tracking and distance on distance estimation and effects	Distance estimation Sickness Postural stability	Silicon Graphics Reality Engine Virtual Research Flight Helmet VE = subset of VEPAB tasks	48 participants (36 male, 12 female) aged 18–50	Significant increase in all SSQ scores. Higher nausea change for stereo viewing. Positive correlation between post immersion SSQ and performance (time). No change in postural stability
9	Goertz et al. (1996)	General discussion of usability issues after first use of VR	Ergonomics exploratory investigation	2∗486 PCs, sense cover HMD with "flying joystick" VE = walkthrough virtual shopping mall	6 female students of media management	Low technical quality criticised. HMD = heavy and uncomfortable. Some sickness experienced, also dislike of collision boundaries Fear of psychological effects of VR—use of VR to escape from real world and lack of ability to distinguish between reality and VR
10	Howarth (1999)	Measuring oculomotor changes after being immersed in VEs using three different HMDs	Distance heterophoria using a Maddox Rod	Virtual I-Glasses with a 486 PC (presented images bi-ocularly and non-stereoscopically) Virtuality/IBM Elysium with Virtuality Visette II HMD (presented images bi-ocularly and non-stereoscopically Division Provision 100VPX with a VISOR HMD (images presented stereoscopically)	41 (32 male, 9 female) aged 19–56	The Virtual I-Glasses and Division systems induced exophoric changes (eyes turning outwards) Virtuality system induced esophoric changes (eyes turning inwards)

Table 2 *(continued)*

	Authors	Experiment description	Effects measured	VR system and VE	Participants	Results
11	Howarth and Blackmore (2000)	Effect of repeated VE immersion on simulator sickness	Sickness	Virtuality Dynovisor HMD (without head tracking) VE = intensive driving game 'Wipeout' run on a Sony PlayStation	7 (4 male, 3 female) aged 19–25	Overall, the severity of reported symptoms decreased on successive days over a 2 week period, but there was an increase after the 2-day weekend break in the experiment. The time that elapsed prior to reporting any change in symptoms increased on successive days, but decreased after the weekend
12	Igarashi et al. (1994)	Physiological, neurological, biochemical and psychological effects of VR use	ECG response	Silicon Graphics	20 young male volunteers	No change in physiological parameters or CFF. No change in catecholamines, no change in subjective fatigue. Some reports of sleepiness
			Blood pressure	LCD "home-made" HMD (stereoscopic)		
			CFF	VE = hyper-hospital (psychological interview)		
			Auditory response Catecholamine analysis Mental performance Subjective fatigue			
13	Kline and Witmer (1996)	Effects of system-related cues (wall texture, texture resolution, display FOV and distances) on distance estimation	Distance estimation	Silicon Graphics Crimson	28 (14 male, 14 female) students	Consistent underestimation of distances in wide FOV and overestimation in narrow FOV. Most accurate estimation occurred with rich, fine resolution textures
			Error of estimates	Fakespace BOOM2C with no head tracking		
14	Kolasinki (1996)	Prediction of sickness on basis of age, gender, mental rotation ability and pre-exposure postural stability	Sickness	75 MHz Pentium with Virtual IO I-Glasses and mouse	40 students (20 male, 20 female)	Sickness occurred after VR use. Participants (30%) also experienced lingering effects and/or after effects. Relationship (complex) between age, gender, mental rotation ability and pre-immersion postural stability with sickness. No change in postural stability
			Postural stability	VE = ascent		
15	Kolasinksi and Gilson (1999)	Investigated postural stability following VR exposure	Postural stability (tandem Romberg)	PC-based system 75 MHz Pentium with Virtual I-Glasses	40 (20 male, 20 female) aged 19–46, mean age 22.7	Post-exposure SSQ scores were higher than pre-exposure scores
			Sickness	VE = game consisting of rock-jumping through canyon walls	Students	No differences between pre- and post-exposure ataxia

16	Kotulak and Morse (1995)	Examined relationship between oculomotor response (accommodation and convergence) and symptoms	Clinical visual symptom Focus adjustment	AH-64 Apache Helicopter HMD	13 Apache Helicopter pilots	Different oculomotor responses for symptomatic and asymptomatic participants
17	Lampton et al. (1994)	Comparison of spaceball and joystick over practice in VE	Task performance Sickness	Virtual Research Flight Helmet 2∗486 PCs (stereoscopic display) with joystick or spaceball VE = Virtual Environment Performance Assessment Battery (VEPAB)	24 participants (main experiment) 6 participants (practice effects)	Joystick generally better controller although difference between spaceball and joystick diminished over time (i.e. after practice). Some reports of sickness
18	Lampton et al. (1996)	Comparison of HMD and BOOM with standard computer monitor	Postural stability Sickness Visual acuity (in VE) Height and distance estimation	Silicon Graphics with BOOM, Flight helmet or 20″ monitor	48 students (24 male, 24 female)	Visual acuity performance best on monitor, then BOOM, then HMD. Significantly greater underestimation of height on HMD than monitor. Fastest performance on search task on monitor, then HMD, then BOOM. No significant difference in display type for SSQ
19	Lampton et al. (2000)	Measuring simulator sickness during team training in immersive VEs	Sickness	Two Silicon Graphics ONYX with VR4 HMDs VE = buildings, two person shared VE	93 (38 male, 55 female) Students	Symptoms abated after first immersion, then for some participants symptoms increased with subsequent immersions Eyestrain was reported most frequently for each of the five immersions 9% of participants (all female) withdrew because of sickness
20	Lo and So (2001)	Effects of scene oscillations along different axes (pitch, yaw, roll or no oscillation) on sickness	Nausea ratings Sickness	Silicon Graphics ONYX with VR4 HMD VE = buildings, train station, tracks, cables and bridges	16 male university students and staff, mean age 26	Nausea ratings and SSQ scores increased at higher rates in the presence of scene oscillations than with no oscillation Overall effects of oscillations along different axes was not significant

Table 2 *(continued)*

	Authors	Experiment description	Effects measured	VR system and VE	Participants	Results
21	Mon-Williams et al. (1993)	Effect of wearing HMD on binocular stability	Visual acuity	VPL EYEphone LX HMD	20 adults (unpaid volunteers)	Short term lowered visual acuity
			Heterophoria			
22	Mourant and Thattacherry (2000)	Examining whether severity and type of simulator sickness varies as an effect of type of driving VE or gender	Sickness	400 MHz Pentium II with VR8 HMD	30 (15 male, 15 female) aged 18–36	Most symptoms reported were oculomotor discomfort
			Postural stability	VE = virtual driving simulator—three types: highway, city, rural	Students	Participants in the highway (60 mph) or rural road (60 mph) VEs reported more symptoms than those in the city VE (25 mph) In both pre- and post- immersion tests, females had less postural stability than males, and they also reported a greater increase in oculomotor discomfort symptoms
23	Neale (1997)	Effect of Geomteric FOV (three levels), visual momentum (low vs. high) and task difficulty (easy vs. hard) on performance	Cognitive map scores	Virtus walkthrough on Macintosh Quadra 840 AV with 21″ colour monitor	60 university students	Decrease in FOV resulted in spatial orientation and representation errors. As task difficulty increased errors became more pronounced
			Direction judgements Object placement time	VE = virtual building		
24	Nichols et al. (2000b)	Experiment 1: Examining sensory conflict adaptation as a predictor of virtual reality induced symptoms and effects (VRISE)	Sickness	Pentium 166 PC running a Superscape visualiser	80 (40 male, 40 female) aged 18–49, mean age 24.3	Using VE for 30 min resulted in a greater level of oculomotor discomfort than using a VE for 10 min
				Virtual Research V8 headset	Students and non-students	Generally higher levels of symptoms reported when the HMD was used to control direction of movement
				VE = virtual maze VE = Virtual factory		Some evidence that those who adapt quickly to new combinations sensory input experience less sickness
	Nichols et al. (2000a, b)	Experiment 2: Comparison of VRISE in migraineurs and headache free controls	Sickness	Reality theatre	10 males, 5 migraineurs, 5 headache free controls	Over all SSQ sub-scales migraineurs had higher post-exposure scores than controls
				VE = virtual factory		Symptoms were longer lasting for migraineurs, and reoccurrence of symptoms were only reported by migraineurs

	Nichols et al. (2000b)	Experiment 3: Comparison of VRISE in four viewing conditions	Sickness	HMD, desktop, reality theatre, projection screen VE = virtual factory	71 (38 male, 33 female), mainly students	Higher post-exposure nausea SSQ scores for HMD compared with desktop display and Reality theatre Pre-post change in nausea symptoms score for HMD was the highest Post-exposure disorientation higher in HMD than desktop display Pre-post change in disorientation symptoms higher in HMD than in reality theatre Post-exposure total symptom score higher in HMD compared with desktop display
	Nichols et al. (2000b)	Experiment 4: Comparison of VRISE in light and dark viewing conditions	Sickness	Desktop display VE = virtual factory	37 (18 male, 18 female), mainly students	No differences in symptoms experienced in the light and dark conditions
25	Owen et al. (1998)	Relationship between reported susceptibility to motion sickness and postural control whilst viewing a disorienting VR display	Postural stability	Virtual I-Glasses	34 (14 male, 20 female) aged 22–47, mean age 28.9	Postural instability was strongly associated with susceptibility to motion sickness
			Vision and motion sensitivity	Force platform linked to a DELL Gs computer VE = virtual corridor with chequered walls		
26	Prothero et al. (1999)	Experiment 1: Effect of an independent visual background (IVB) and an occluded background on sickness and ataxia	Sickness	Virtual IO I-Glasses	15 (10 male, 5 female) aged 22–44, mean age 31	IVB reduced SSQ ratings and resulted in less ataxia
			Ataxia (sharpened Romberg stance) Vection ratings	VE = circular motion stimulus		Vection ratings were not lower in the IVB condition
	Prothero et al. (1999)	Experiment 2: Effect of an IVB and an occluded background on sickness and ataxia when attention was directed to the content-of-interest (CI)	Sickness	Virtual IO I-Glasses	21 (15 male, 6 female) aged 18–37, mean age 25	Less ataxia in both IVB and occluded conditions in Experiment 2 than in Experiment 1, possibly due to absence of head rolls
			Ataxia	Chattecx Balance System		Condition had no effect on SSQ ratings, but post-SSQ scores were higher than pre-exposure SSQ scores Vection ratings did not differ between conditions
				Platform		Condition had no effect on ataxia but post-exposure ataxia was worse than pre-exposure ataxia

Table 2 *(continued)*

	Authors	Experiment description	Effects measured	VR system and VE	Participants	Results
27	Regan and Price (1993a) (February)	Effect of VR use in population of firefighters	Sickness	Provision 200 with Virtual Research Flight Helmet and 3D mouse VE = corridor leading to rooms containing tasks	50 firefighters (49 male, 1 female)	4 participants (8%) withdrew before 20 min; 42% experienced sickness
28	Regan and Price (1993b) (April)	Physical ergonomics effects of using VR	Subjective reports of equipment and display quality	Provision 200 with Virtual Research Flight Helmet and 3D mouse VE = corridor leading to rooms containing tasks	150 adults from military staff and firefighters	8 participants (5%) withdrew before 20 min. Some problems with equipment highlighted but most users' impressions were favourable
29	Regan and Price (1993c) (July)	Effect of head movements (large vs. small) and viewing position (seated vs. standing)	Sickness	Provision 200 with Virtual Research Flight Helmet and 3D mouse VE = corridor leading to rooms containing tasks	44 military personnel (43 male, 1 female)	No difference between groups (only 10-min immersion)
30	Regan and Price (1993d) (August)	Investigation into relationship between IPD and ocular-related problems	Sickness	Provision 200 with Virtual Research Flight Helmet and 3D mouse VE = corridor leading to rooms containing tasks	53 participants (25 male, 28 female)	Some indication that participants with greater deviation from system configuration when IPD less than system experienced more ocular problems
31	Regan and Price (1993e) (September)	Comparison of results from two immersions in VR	Sickness Postural stability	Provision 200 with Virtual Research Flight Helmet and 3D mouse VE = corridor leading to rooms containing tasks	50 military staff (27 male, 23 female)	No change in pre-post immersion for 2nd immersion 48% participants had decreased levels of symptoms for 2nd immersion. Some symptoms lasted for up to 5 h. No difference between symptoms for users moving at different rates
32	Regan and Ramsey (1994a) (January)	Comparison of results from four immersions in VR	Sickness	Provision 200 with Virtual Research Flight Helmet and 3D mouse VE = corridor leading to rooms containing tasks	30 military staff (18 male, 12 female)	50% participants ceased to report symptoms after four immersions. Marked decrease between 1st—2nd and 3rd—4th immersions
33	Regan and Ramsey (1994b) (November)	Comparison of effect of different types of movement (bike control vs. 3D mouse)	Sickness	Provision 200 with Virtual Research Flight Helmet using either exercise bike or 3D mouse VE = urban environment with cube collection tasks	60 participants—staff and students at University of Reading (55 male, 5 female)	Less nausea reported in seated (3D mouse) group. Worse performance in bike group. Motion sickness history predicted symptom reports

34	Regan and Ramsey (1996)	Efficacy of Hyoscine Hydrobromide in reducing VR side-effects (compared to placebo)	Sickness	Provision 200 with Virtual Research Flight Helmet and 3D mouse VE = corridor leading to rooms containing tasks	39 military staff (33 male, 6 female)	Drug effective in reducing nausea, stomach awareness, headaches and eyestrain
35	Stanney and Hash (1998)	Effect of different degrees of user-initiated control (active, i.e. complete control; active-passive, i.e. coupled control; passive, i.e. no control) on level of cybersickness	Sickness	486/DX2 computer 66 MHz. 3D TV Stereo Space Model 1 shutterglasses	24 college students (14 male, 10 female) aged 16–27	Mean total SSQ severity scores under the active-passive and active conditions were less than under the passive condition
				Tasks developed using Sense8's WorldToolKit		Consistent trend between the control conditions across all symptom types: passive was greater than active which was greater than active–passive
				VE = maze of 18 rooms consisting of locomotion tasks involving doorways, windows and elevators		There was no effect of locomotion task
36	Witmer et al. (1996)	Effectiveness of route knowledge training in VE, actual building or verbal directions with photographs	Route knowledge	Silicon Graphics CRIMSON with BOOM2C	64 UCF students (30 male, 34 female)	4 participants withdrew due to sickness. VE more effective than verbal rehearsal with pictures, less than real world walkthrough. But spent overall longer time in VE. No relationship between sickness and performance. Presence negatively correlated with sickness
			Configuration knowledge Sickness Presence			

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[a] Two separate experiments were presented in this paper.

(1996) report that Bailey (1994) found that a head coupled display appeared to increase simulator sickness symptoms, but in their own study found no difference between symptoms of participants whose head movements were either tracked or not. Tiande and Jingshen (1991) quote Dichgans and Brant (1973) as suggesting that experiences of motion sickness were related to the speed of a moving scene and head movements, but Lackner and Teixera (1977) found participants in head moving conditions were less sick.

Sensory conflict theory would suggest that a lower level of symptoms should be experienced if head coupling is present, as this removes some visual-inertial conflict. However, the reason for the conflicting research results could well be that, whilst the movement of the head is reinforced by a change in the visual scene, there is some lag present and therefore not all sensory conflict is eliminated. It should also be remembered that the movement of the head involves increased vestibular stimulation, and this movement, especially if symptoms are already being experienced, could well increase symptom levels regardless of the visual-vestibular conflict. Biocca (1992) agrees with this, suggesting that symptoms could result from the coupling of the perceptual system to the physical world not being matched smoothly. These mismatches include: position tracking error (i.e. proprioceptive—visual mismatch); lag in updating body position; jitter or oscillation of represented body parts. It is also suggested that distorted graphics, poor optics, image flicker and off-axis viewing may contribute to symptoms. Piantanida et al. (1993) point out that VR HMDs have lower spatial and temporal resolution than the human visual system which results in a necessary compromise between FOV and resolution. A minimum 12 Hz frame rate is recommended. It is also suggested that a delay of 100 ms "can cause distracting movement illusions and even motion sickness". The degree of inaccuracy of position trackers may also determine the extent of sickness symptoms. These trackers may also cause jitter, and these problems may cause dizziness and result in a lack of concentration (La Viola, 2000).

Projection quality has been associated with sickness symptoms, and is affected by a number of factors; important ones are FOV, flicker and frame rate. FOV is defined by the horizontal and vertical angular dimensions of a display (Pausch et al., 1992), and its role in inducing sickness symptoms during VR immersion has been examined in several studies. Some researchers have suggested that restricting the FOV may reduce the incidence of sickness (e.g. Biocca, 1992; Kennedy et al., 1989). Wide view visual displays appear more likely to produce vection (illusory feelings of self-motion which are thought to contribute to sickness). Sensory conflict theory predicts that more conflict would be present with a wider FOV, and therefore more sickness would be expected. However, sickness symptoms have also resulted from viewing narrow displays suggesting that it may be the presence of conflict that is of primary importance, and the degree of conflict is a secondary issue; symptoms have been found to occur from viewing displays of as little as 7.5° (Andersen and Braunstein, 1985).

Flicker is more likely to be perceived as the FOV increases (Maxwell, 1992). This is because a wide FOV will lead to increased stimulation of the peripheral retina which is more sensitive to flicker than the fovea (Boff and Lincoln, 1988). A faster refresh rate for wider FOVs can help to avoid flicker. Flicker has been associated with eye fatigue and sickness (e.g. Pausch et al., 1992). Luminance levels are also associated with flicker; a high level of luminance is related to greater flicker. Flicker can induce seizures (Wilkins et al., 1979); it is therefore important to minimise the negative effects of flicker from viewing projection screens in order to reduce the likelihood of side effects.

Frame rate is defined as the speed of the simulation, or the speed at which successive frames of a moving scene are generated for display (Pausch et al., 1992). Slow frame rates can lead to visual lag, which has been linked with sickness.

Ehrlich and Singer (1996) compared symptoms after viewing a VE in stereoscopic and monoscopic headsets and found that the stereoscopic condition was more nauseogenic. HMDs have also been found to cause changes within the oculomotor system. Howarth (1999) showed that heterophoria ('motor imbalance of the eyes where the passive, fusion-free, position of the eyes deviates from the active position' (p. 60)) changes after using VR headsets, but these changes are likely to be due to the different optical configurations of the equipment. Other factors which have been implicated in heterophoria changes after headset use are prism adaptation, and the possibility that HMDs can induce transient myopia.

Other experiments manipulating VR technical variables have suggested concern with postural instability. In an experiment carried out by Kennedy et al. (1993a, b) post-exposure postural instability was inferred from a *reduction* in postural stability *improvement* that was significantly less than in a control group. The implications are that on the one hand, a change in behaviour was found (a reduction in postural stability improvement), and on the other hand no actual performance deficit was identified and therefore there is no safety concern. This study was conducted in flight simulators; VR-based studies conducted by Regan and Price (1994) and Kolasinki (1996) did not find conclusive evidence of postural instability. Kolasinki (1996) interpreted her result as indicating that it was the passive nature of the VE task, in which movement was generally in a forward direction, that meant no postural instability was induced.

Other main human factors issues of concern for VR system design are postural difficulty and physical discomfort. These are associated with design of HMDs and handheld input devices (see Nichols, 1999a).

3.2. VE characteristics

The VE characteristic related to the effects of VR participation that has been studied in most detail is *vection*. Hettinger et al. (1990) suggest that vection is a necessary precursor to simulator sickness. Kennedy et al. (1989) and Ehrlich and Singer (1996) support this view. Biocca (1992) states

> Illusory feelings of self-motion (vection) usually precede… sickness (Biocca (1992))

McCauley and Sharkey (1992) suggest a dual role of vection; it may increase presence but may also be necessary to induce simulator sickness. This obviously has implications for the relationship between presence and sickness. One consequence of vection being a causative influence on sickness production could be that users minimise head movements (and thus their level of perceived vection) to avoid nausea (Hettinger et al., 1987). Lee et al. (1997) examined the correspondence between reports of experienced vection and sickness. They showed a tendency for those who experienced vection to also be sick, but due to low participant numbers (11), almost all of whom reported sickness, it is difficult to draw strong statistical conclusions from this study.

McCauley and Sharkey (1992) distinguish between the potential effects of "near" and "far" applications. Near applications, such as those used in automotive design or virtual representation of medical procedures, involve only limited head movements, and the absence of whole body rotation and linear acceleration. Objects are close to the user, and hence there will be little vection. In contrast, the motion present in far applications (e.g. terrain examinations and driving and flight simulators) provides more cues to induce vection, resulting in greater likelihood of a lack of corroboration of visually represented motion with vestibular signals (La Viola, 2000; McCauley and Sharkey, 1992). Therefore McCauley and Sharkey (1992) conclude that motion sickness is only likely in far applications, unless near applications require excessive head movements.

The semantic content of the visual images presented within the VE, and the familiarity of these images, may have an effect on the incidence of sickness. From research examining habituation (lower levels of symptoms on repeated exposure to stimuli) in VEs (see below), it seems reasonable to assume that we may experience fewer side effects whilst viewing images which are familiar to us than those which are unfamiliar. In accordance with the role of expectancy in sensory conflict, people may be 'prepared' for the sensory conflict situation to be encountered (i.e. the familiar images), and thus experience a lower level of symptoms.

Prothero et al. (1999) suggest that motion sickness arises from conflicting rest frames selected from conflicting motion cues. Rest frames are defined as 'the particular reference frame (a co-ordinated system used to define positions, angular orientations and motions) which a given observer takes to be stationary' (p. 277). As the visual background usually provides the majority of coherent cues in the environment, it follows that the visual background should strongly influence the visual rest frame which is selected. Prothero et al. (1999) found that providing an independent background which is consistent with inertial cues reduced simulator sickness and ataxia even when the foreground cues (i.e. the VE's content-of-interest) are not in agreement with the inertial rest frame. In addition, post-exposure vection ratings (e.g. in answer to the question 'While in the VE, did you get the feeling of motion?') were not affected by using an independent (see through) visual background as opposed to an occluded background. This suggests that an independent visual background can reduce sickness symptoms without detracting from feelings of presence in the VE.

In Mourant and Thattacherry's (2000) study, participants used a VE driving simulator. Participants experienced one of three different driving environments; highway (60 mph), rural (60 mph) or city (25 mph). The SSQ and a postural stability test were administered pre- and post-immersion. Participants drove the simulator wearing a HMD for 5 min. In contrast to previous studies (e.g. Kolasinski and Gilson, 1998; Ehrlich et al., 1998; Stanney and Kennedy, 1998) most of the reported symptoms fell into the oculomotor discomfort category (eyestrain, headaches, difficulty focusing and blurred vision). Vehicle velocity appeared to encourage sickness symptoms, as participants who drove 60 mph in the highway or rural road environments reported more symptoms than those who drove 25 mph in the city environment. This may be due to the increased rate of global and visual flow in the higher velocity environments (see below and McCauley and Sharkey, 1992). In both the pre- and post-immersion tests, females were less posturally stable than males, and they also reported a greater increase in oculomotor discomfort symptoms than males.

Lo and So (2001) examined the effects of rotational scene movements along different axes on the level of VR-induced sickness. Scene oscillations in the pitch, roll and yaw axes result in vection, which is associated with sickness. Participants were exposed to four different conditions (no scene oscillation, and scene oscillations along the pitch axis, yaw axis, and roll axis) for 20 min each. Mean nausea ratings increased with increasing exposure time, and the presence of scene oscillation along the pitch, yaw and roll axes increased the rate of nausea ratings with duration. Lo and So's (2001) results suggest that scene oscillation can induce sickness, and this is consistent with the sensory conflict theory which predicts that vection can result from exposure to wide FOV scene movement, which is associated with sickness symptoms (Reason and Brand, 1975). Examination of the post-exposure SSQ sub-scores showed that in the three conditions with scene oscillations, oculomotor scores were higher than disorientation sub-scores, which were higher than the nausea scores. This pattern is consistent with that reported in three experiments by Cobb et al. (1999). The overall effects of oscillations along the different rotating axes were not significant.

Another aspect of visual content which may induce sickness symptoms is the degree of complexity in the images. Theories of vection and its association with sickness would suggest that VEs with high numbers of textured images and large amounts of movement would induce a high level of vection, and therefore a high level of reports of sickness symptoms. Complex VEs may result in a higher level of optic flow (changes in the visual world) which can induce vection since a faster flow rate will increase the speed of the perceived motion, thus intensifying the illusion of self-motion (La Viola, 2000). The consequence of this is that a higher level of sensory conflict will exist between the information presented to the visual system and associated vestibular or proprioceptive input.

3.3. *Task circumstances and characteristics*

Several "task circumstances" have been identified as potentially having an effect on sickness symptoms. Pausch et al. (1992) suggest that the position of a user in relation to the stimuli (e.g. pilot vs. co-pilot in a simulator) could influence symptoms experienced. McCauley and Sharkey (1991) found that the longer pilots were exposed to the flight simulation, the greater the risk of symptom development, particularly if the pilots had not adapted to the simulated environment.

Kennedy et al (1995) note:

> Kennedy and Fowlkes (1990) have shown that as much as 25% of the variance in simulator sickness... can be attributed to hop length and this effect, to a large extent, is independent of other equipment and usage characteristics.

Positioning users in the VE may also affect susceptibility to sickness. Viewing VEs in a sitting position may reduce sickness symptoms as this reduces the demands on postural control. In a multi-user collaborative VE, users who control the simulation have been found to be less susceptible to sickness than passive users (La Viola, 2000). Stanney and Hash (1998) also found that when users are able to control their own movements in VEs the severity of reported sickness symptoms are lower than when users have no control over their movement. A coupled control VE was most successful in reducing the severity of symptoms experienced (see also Nichols et al., 2000b).

The activities completed by a participant during immersion may also influence any symptoms they experience. Regan and Price (1993c) compared different head movements and viewing positions for a 10 min VR immersion and found no difference between groups. However, Regan and Ramsey (1994b) found that less nausea was reported by participants who were seated whilst moving around a VE compared with participants who used an exercise bike to move around the environment.

Regan and Price (1993e) examined habituation in VEs and found that 48% of participants had decreased levels of symptoms on a second immersion. Biocca (1992) also found evidence of habituation, although he estimated that around 3% of the population may never adapt. But Gower et al. (1988) found an inverse relationship between sickness symptoms in simulator users and postural equilibrium over repeated exposures where symptoms decreased, but there was no change in postural equilibrium. These results support the role of expectancy in sensory conflict. In addition, Kennedy et al. (2000) found that exposure duration was positively related to sickness symptoms, and repeated exposure was negatively related to sickness, suggesting that participants habituated to the VE. Further research is required to find the optimal length of exposure to a VE to minimise sickness symptoms whilst facilitating habituation.

However, Howarth and Blackmore (2000) found that whilst repeated exposure to a VE reduced the incidence of sickness symptoms, a break in the sensitisation process (i.e. when there was a longer inter-session interval) lead to a reoccurrence of symptoms when immersed in the VE. Lampton et al. (2000) used a fully immersive team training research system to allow two participants to conduct building search missions in up to five VEs. They found that after the first immersion, participants reported some symptoms, but there was evidence of adaptation due to a fall in reporting of symptoms after the second immersion. However, some participants reported an increase in symptoms with later immersions. Eye strain was the most frequently reported symptom after all five immersions.

Characteristics of the environment in which immersion is experienced may also have an effect on sickness. For example, high temperatures may lead to feelings of discomfort, and may provoke sweating and have an impact on stress levels. Anecdotal evidence from experiments carried out by the authors at the University of Nottingham suggests that if VEs are viewed in warm and uncomfortable conditions then symptom levels may be higher and symptom onset more rapid.

3.4. Individual participant characteristics

Individual characteristics have been highlighted as an influence on the type and severity of simulator or VR-induced sickness symptoms that might be experienced (Kennedy et al., 1996; Hettinger et al., 1987). Some people report symptoms in certain VEs whereas others in identical conditions do not. Biocca (1992) suggests that relevant characteristics may include age, gender, experience, neuroticism, anxiety, arousal, introversion and perceptual style. He also suggests that individuals who are highly receptive to sensory information are more likely to become motion sick, and those who are highly adaptive quickly adapt to sensory rearrangements and are therefore less likely to experience motion sickness and simulator sickness.

Kolasinski (1996) conducted a study examining a number of individual characteristics and found that a complex relationship existed between age, gender, mental rotation ability, pre-immersion postural stability and sickness. However, the exact nature of the relationship was not clear due to the interactions between variables as indicated by a linear regression equation.

McCauley and Sharkey (1992) also suggested that pilots may well be less susceptible than the general population, due to "self-selection". Therefore, prevalence in the general population may be higher than has previously been found in studies where a military population has been used.

Individual differences in user behaviour have also been suggested to affect symptoms experienced. Biocca (1992) suggested that users who experience sickness may change their behaviours (e.g. head movements) to minimise those movements that accentuate the visual proprioceptive conflict. However, when considering head movements, Pausch et al. (1992) make the point that if the FOV of a display is smaller then more head movements may be required to complete tasks. This is an interesting example of the potential interactions between different influential variables: research suggests that a smaller FOV should decrease vection and therefore sickness, but if increased head movements lead to increased sickness (as suggested by Graybiel and Johnson, 1963) then the smaller FOV could *indirectly* lead to *increased* sickness.

Tiande and Jingshen (1991) found that different vection and head movement combinations produced different levels of sickness. However, Regan and Price (1993e) found no difference between symptoms for users moving at different rates.

Several inherent characteristics have also been implicated. There appears to be a gender effect; some researchers have suggested that females may be more susceptible to sickness than males (Kennedy and Frank, 1983; Lampton et al., 2000). A possible explanation for this difference is that females generally have a wider FOV than males, which increases the likelihood of flicker perception (La Viola, 2000). Previous research has found that young male drivers were insensitive to simulator sickness, whereas older female drivers were generally susceptible (Swezey et al., 1995). Kennedy and Frank (1983) believe that age has an influence on sickness susceptibility; susceptibility decreases until people reach the age of 50. Some researchers have found that susceptibility to motion sickness in general is greatest between the ages of 2 and 12 years, and decreases rapidly from 12 to 21 years, and then decreases more gradually (Reason and Brand, 1975). Reason and Brand (1975) report that sickness is very rare around 50 years of age.

One physical characteristic that has been suggested to have an effect is inter-pupillary distance (IPD). Regan and Price (1993d) found some indication that participants with a greater deviation from the system configuration, when IPD was less than the system setting, experienced more ocular problems.

Kennedy and Frank (1983) suggest that a person who is ill before immersion may be predisposed to experience a higher level of negative effects. Pausch et al. (1992) also highlight previous experience of the stimuli as having an influence, where those with more experience are likely to exhibit a lower level of symptoms. In addition, participants' adaptation state may influence symptom experiences, meaning that symptoms may decrease during a long immersion (McCauley and Sharkey, 1991).

Finally, previous history of, and susceptibility to, motion sickness have frequently been suggested to be predictors of sickness symptoms. Lampton et al. (1995) found that some participants who rated themselves as susceptible to motion sickness experienced higher levels of symptoms. Regan and Ramsey (1994b) found that motion sickness history was a predictor of symptom reports. Gower et al. (1988) also found a relationship between motion sickness susceptibility (measured by questionnaire) and simulator sickness susceptibility. These studies used questionnaires to measure previous motion sickness history. There are also a number of clinical measures of sickness susceptibility, that generally involve the presentation of a severe stimulus to the participants over a short period of time, and measurement of the symptoms elicited.

4. Management of health and safety implications of VR

On the basis of the empirical evidence, it is apparent that the main effect of concern which has been examined in the literature is VR-induced sickness. In order to

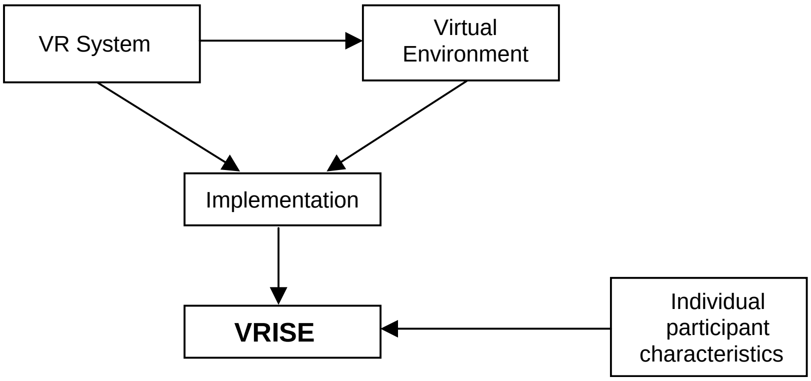

Fig. 1. Impact of influential factors on VRISE.

ensure that research can be the basis of guidance for those developing and using VR, the way in which the different influential factors interact should be specified.

Fig. 1 illustrates the relationship between the four influential factors. VR system and VE design both contribute to the effects experienced. It is also likely that VR system characteristics may affect VE design (e.g. if a high processor speed is available then the developer may include more textures in the VE). These two factors are both then implemented in the situation in which the VR application is to be used. It is at this stage of implementation that the task circumstances, such as training given to the participant or environmental conditions in the room, are determined. It is this implemented system that will be presented to the user, and will interact with the individual participant characteristics to produce the effects experienced. The term VRISE describes the multi-factorial and interactive nature of all the different effects that may be experienced by a participant.

A concept that has previously been proposed is the *virtual experience*—a term intended to encompass the combination of effects experienced by the user. The virtual experience is subjective and is likely to have an impact on participants' individual characteristics.

The virtual experience could impact the user in a number of ways. Firstly, a user's experience of VR could affect their attitude, and therefore their attitudes to any future use of the technology. Secondly, the experience may affect user behaviour, during the initial VR use and on future occasions. For example, if a participant found that they experienced lower levels of sickness by minimising their head movements, they may continue to minimise head movements in future use of VR. This may in turn affect performance in the VE. It is also possible that the experience of VR use may actually cause a physiological change in the participant. This may lead to habituation—where participants experience decreased levels of sickness after an initial immersion. This process is illustrated in Fig. 2. Any effect experienced is interpreted by the participant. Once this interpretation has occurred, the participant may choose, either consciously or subconsciously, to modify their behaviour, as in where participants have been observed to minimise head movements to reduce sickness symptom levels. This behaviour change can have an immediate impact on the effects experienced, as shown in Fig. 2 by the feedback loop from behaviour to VRISE.

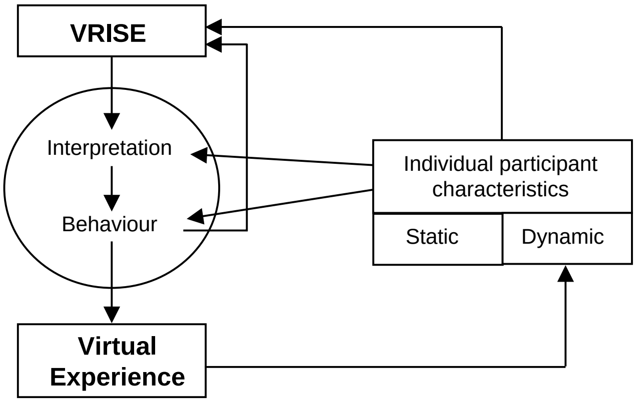

Fig. 2. Impact of VR use on individual participant characteristics.

It can also be seen that individual participant characteristics will have an impact at several stages in the process. Gender, attitude or skills may directly affect the levels and types of effects experienced. In addition, individual psychological differences may cause VRISE to be interpreted in different ways, and different behaviours to be adopted. The type of individual differences in behaviour can be likened to coping strategies. Individuals can be informed about the effectiveness of various coping strategies, and may have personal preferences that influence which coping strategy is chosen.

Some individual characteristics will not change, and may have a consistent influence on the virtual experience. These are classified as *static* individual

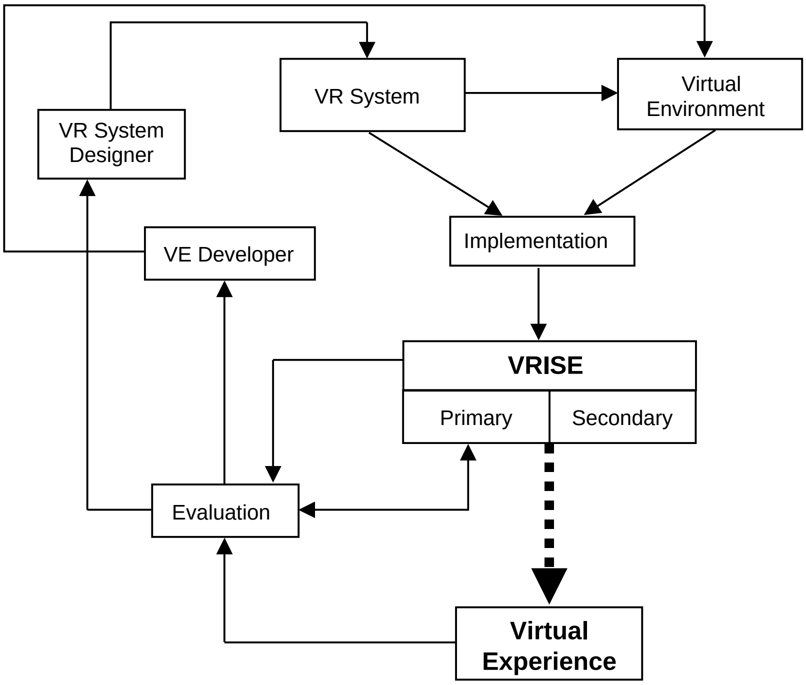

Fig. 3. Evaluation of VRISE.

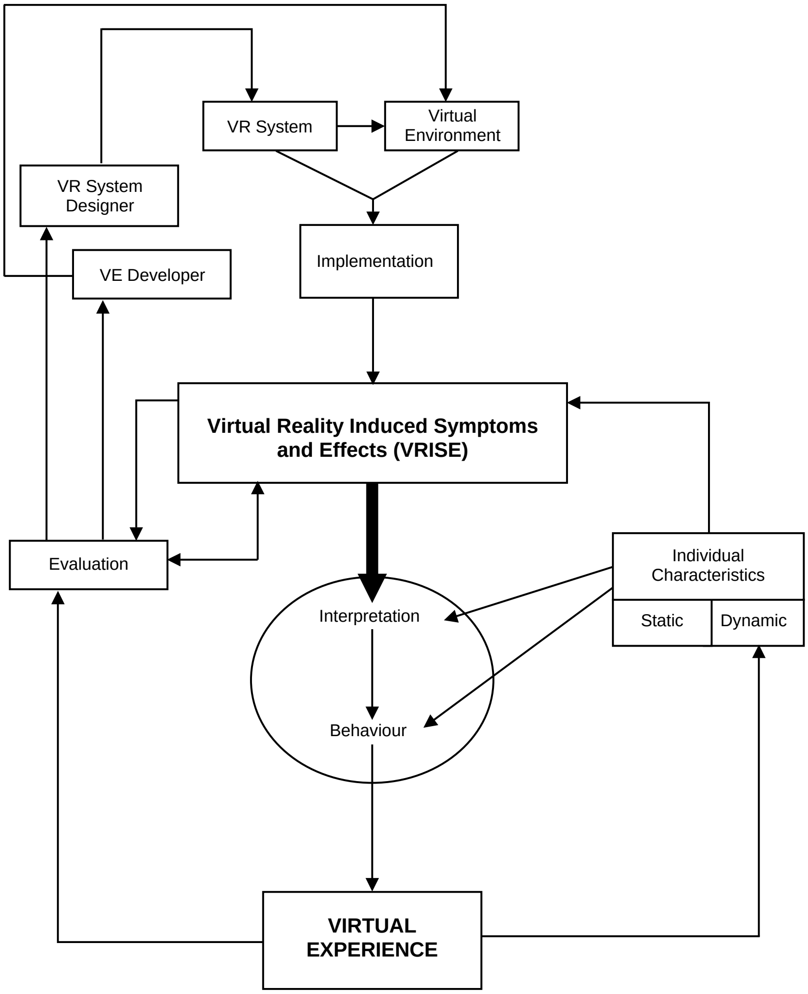

Fig. 4. Model for management of VRISE.

characteristics. Examples of these include both permanent characteristics such as gender, and those that change slowly over time, and are unlikely to be influenced by intervention of training or education, such as age or personality. However, there are other types of individual characteristics—dynamic ones. These include transient factors, such as state of health, and those that may be affected by training or education, such as skills with input devices, attitudes and experience with VR or technology in general. If it is found that static individual characteristics affect the virtual experience, then these cannot be changed and negative effects should be minimised by manipulation of the VR system, the VE, or the way in which VR is implemented. If, however, dynamic individual characteristics are found to have an influence on VRISE, it may be appropriate to use training or other support to modify that characteristic and minimise any negative effects experienced.

Finally, it is important to identify the role of evaluation, and the appropriate ways in which results of empirical research should be communicated to the VR community in general. Fig. 3 shows the process of feedback of the results of evaluation into the VR system and VE design process. The main source of information to be evaluated is from the virtual experience—by both subjective reports and performance assessment. However, it is also possible to evaluate effects directly (e.g. by physiological measurement techniques). This is shown by the arrow leading directly from effects to evaluation.

The third potential source of evaluation data is that which is possible by automatic monitoring built within the VE. Primary effects, such as performance, may be monitored in this way, and changes immediately made to the VE in order to encourage effective performance. This is shown by the two-way arrow linking primary effects of VR use and evaluation.

The results of evaluation should be fed back into the design process, by producing guidelines for VE and VR system designers.

Fig. 4 shows the integration of the three models presented earlier into a model for management of VRISE. Guidelines for design should be applied to the VR system and VE. Guidelines for the way in which VR should be used, including recommendations as to the length of immersion period, types of incentives provided to participants, or the integration of VR within the work environment, should be applied during implementation. Training of participants may affect dynamic individual characteristics.

5. Conclusions

The research and models presented in this paper aim to show how the different aspects of VR design and use are linked, with specific reference to the experience of side and after effects. The models will support the specification of appropriate research methods, topics and approaches in the future. Whilst empirical research has established that participants may experience sickness as a result of VR use, it is not yet clear exactly what causes the symptoms, probably because of the interactive nature of the influential factors.

VR is being used increasingly in a number of work contexts, such as the automotive industry, architecture and medicine, and so it is important that future research takes into account the way in which VR is being used. The first way that this can be achieved is to ensure that studies *consider both effects and their consequences*. This applies both to objective or direct measures such as physiological or performance monitoring, and self-report measures. For example, is it possible to establish the implications of an increase in a VE participant's body sway of 50 mm over a 30 s measurement period? Or can we identify a maximum heart rate that should be experienced by VR participants? Obviously, the definition of such parameters would involve a large amount of data collection to ensure that all individual participant characteristics and variations in other influential factors could be accounted for—probably making this an impossible aim.

For self-report measures, it may be possible to specify a recommended maximum number of reported symptoms that indicate that someone is experiencing such a high level of symptoms that they are considered to be a problem or of concern. In this case the individual differences may be manifest in traditional subjective response biases.

One way to address this problem more quickly is to apply multiple methods, including ones that ask participants directly to estimate how debilitating they would find the symptoms or effects that they are exhibiting or reporting if they were in a workplace. However, this would not be appropriate for the measurement or anticipation of longer term, cumulative effects or those that may have delayed onset or consequence.

A second approach is to *ensure that empirical trials reflect the actual likely context of VR use*. Experimental participants should have the same individual characteristics and receive the same level and type of training as potential users, in addition to making sure that laboratory trials are conducted on equipment that reflects that being used in real applications.

A third requirement is to *consider interactions between effects*. For example, a more photorealistic environment may increase the sense of presence experienced by the participant, but may also increase the extent of sensory conflict between the visual and vestibular system, and thus increase symptoms. Similarly, the experience of sickness could distract the participant from the VE, and thus reduce their sense of presence. It is important that we establish that if any negative symptoms or effects are measured, how these interact with other effects to produce the overall virtual experience.

Finally, we should *consider ways in which effects can be managed*. This may require acknowledgement of the fact that some individuals will almost inevitably experience negative effects, and focus on ways to minimise the consequences of those effects. This may involve careful design of VEs and task requirements (e.g. to minimise level of optic flow), training participants to use input devices, or education about behaviour to minimise the impact of negative effects.

For the majority of VR participants, the positive aspects of VR use, such as improved visualisation performance, motivation or enjoyment, may outweigh any negative effects experienced. As technology develops, some effects may lessen, but some may still remain or even become more pronounced. Therefore, a forward looking approach is required that allows empirical studies to continue but ensures that empirical data can be converted into guidelines as required. In this way we will be able to address the human factors issues associated with VR use in a systematic and useful manner.

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