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Virtual Reality-Induced Symptoms and Effects (VRISE)

Abstract

An experimental program of research was carried out to assess the potential health and safety effects of participating in virtual environments (VEs) via head-mounted displays (HMDs). This paper presents the results obtained from nine experiments examining the effects experienced during and after participation in a variety of VR systems, VE designs, and task requirements, for a total participant sample of 148 individuals. A combination of methods including self-report scales, performance measures, physiological indicators, observation, interview, and user attitude/opinion questionnaires were used to measure simulator (VE) sickness, postural instability, psychomotor control, perceptual judgment, concentration, stress, and ergonomics effects. Greatest effects across the different systems, VEs, and exposure times were found for sickness symptoms and physiological measures, with some concern over postural instability and physical ergonomics, also. Although many of the effects were relatively minor and short lived, they were serious for five percent of participants and irritating for a considerable percentage more. The aetiology of the effects is sufficiently different to that for simulators or transport systems to justify us using a new term, *virtual reality-induced symptoms and effects* (VRISE). Implications are drawn for VR system design, VE specification, and the ways in which industrial use of VR/VE should be planned and supported.

1 Introduction

Developments in commercial virtual reality (VR) systems for leisure use during the early 1990s aroused interest in potential industrial application. In parallel, press speculation (e.g., Arthur, 1992; Greenfield, 1994) and some scientific studies (e.g., Mon-Williams, Wann, & Rushton, 1993) suggested possible harmful consequences of virtual environment (VE) participation, especially using head-mounted displays (HMDs); all this earlier literature is reviewed in Wilson (1996). Before any potentially hazardous technology was implemented in workplaces, the UK Health and Safety Executive commissioned a two-year program, ''Health and Safety Implications of Virtual Environments'' from the Virtual Reality Applications Research Team (VIRART).

This program addressed potential industrial health and safety advantages as well as side and aftereffects of VE participation. Because of the concentration on health and safety at work, our concern was not only with possible illness, distress, or discomfort during and after participation, but also with changes in, for instance, perception, concentration, and stability, which might interfere with subsequent work performance.

Section 2 summarizes some of the background to the work, especially refer-

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ring to simulator sickness and theories of sensory conflict from related fields. The experimental approach and methods are then summarized in Section 3, and Section 4 presents the major findings. Section 5 then interprets the findings in terms of their implications for VR systems and VE design. The conclusions in Section 6 address the need for, and difficulty of providing, a theoretical framework, and the feasibility of producing guidelines for VE participation.

2 Background

The most widely accepted theory of motion sickness that has been applied to simulator and VR use is the sensory-conflict theory (Reason & Brand, 1975; Regan, 1994; Kolasinski, 1996). Simulator sickness is a specific type of motion sickness that is primarily visually induced (Hettinger & Riccio, 1992). Whilst the main symptoms of motion sickness tend to be nausea, vomiting, and retching—and extreme drowsiness in the case of sea sickness—other symptoms (such as pallor, sweating, salivation, apathy, headache, stomach awareness, disorientation, postural instability, and residual aftereffects) tend to be more prominent in people experiencing simulator sickness (Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992).

Sensory-conflict theory proposes that symptoms occur as a result of conflict between signals received by the three major spatial senses: the visual system, the vestibular system, and nonvestibular proprioception. The two pairs of conflicting receptors proposed (Reason & Brand, 1975; Regan, 1994) are

a) Visual-inertial conflict, in which discrepancies exist between the sense modalities of vision and both the vestibular senses and nonvestibular proprioceptors, and
b) Canal-otolith conflict, in which conflict occurs within the vestibular system, between the otoliths that signal the head's position with relation to gravitational force, and the canals that sense angular movement of the head, and are unaffected by gravity.

Three types of conflict can occur: Type I, in which two conflicting receptors signal contradictory or uncorrelated information; Type II, in which one receptor signals in the absence of an expected signal from the other; and Type III, in which the opposite of Type II occurs. Kennedy et al (1992) suggest that the strong similarities between flight simulators and VEs should produce the same types of problems experienced in simulators in ''any VE in which a compelling sense of presence and self-motion throughout the simulated environment are experienced by the user.'' However, in practice, different types and qualities of VR systems may actually produce different levels and types of sensory conflict. Oman (1993) in fact suggests that what is happening is a ''sensory rearrangement'' due to conflicts between sensed information and previous experience or motor intentions.

Regan (1994) suggests that VR in HMDs induces sensory conflict, since movement in a VR system is primarily controlled by a hand device, so that feedback from the visual system suggests more movement than is implied by the vestibular system's response. There is also the issue of sensory conflict caused by system, tracker, and optics lags, in which the vestibular system signals a movement that is not immediately registered by the visual system. Furthermore, the low resolution of an LCD display may result in insufficient visual cues being provided.

3 Experimental Approach

Any experimental program to assess the effects of VE participation faces immediate and critical problems. Before any links between causative factors and resultant effects can be examined, the experimenters must deal with

- a very large number of potential influencing or causative factors,
- unknown interactions between these factors,
- a large number of overlapping categories of potential effects,

- a wide range of candidate methods and measures (applied from different research fields), and
- possible interference between these methods.

An important aspect of the research was therefore concerned with selecting appropriate methods and measures; methods for measuring VR / VE effects should be capable of identifying whether effects exist, of measuring the degree of effects experienced, and aiding the understanding of any causative factors (Nichols, Cobb, & Wilson, 1997). A program of nine experiments was carried out during this research (with a further three specifically addressing visual symptoms and performance carried out in collaboration with the Visual Ergonomics Research Group of the University of Loughborough (Howarth, 1999). This allowed examination of different configurations of VR systems, VE designs, and task requirements.

The nine individual experiments examined specific effects such as psychomotor performance (Cobb, Nichols, & Wilson, 1995), concentration (Nichols, 1996), postural stability (Cobb & Nichols, 1999) ergonomics (Nichols, 1999), physiological change (Ramsey, submitted), and measures of simulator (VE) sickness were applied in all experiments. The details of each experiment are summarized in Table 1. Technical specifications are provided in Table 2.

A total of 148 civilian participants were used in the experiments. Participants were drawn largely from university personnel and included undergraduate and postgraduate students, and research and administrative staff. The age range was eighteen to fifty (men and women) and represented a reasonably broad skill base and experience of computers. Participants were screened to exclude those with previous experience of VR systems and, with the exception of the experiments that applied repeated trials, took part in only one experiment.

Two main types of virtual environment designs were used in the experiments: those which allowed the participant full freedom of movement around the VE and required them to complete specific tasks such as finding and moving objects (House I, House II, Gallery, Medical, Factory), and those which allowed forward vection only, but with participant freedom over head movement (Zone Hunter, Hospital Corridors).

3.1 Simulator Sickness Symptoms

Two scales were used to assess the participants' experience of symptoms during and after immersion. The Simulator Sickness Questionnaire (SSQ) is an established measure that is consistently used in much research on simulator use, and is now being applied widely in VR / VE research (Kennedy, Lane, Berbaum, & Lilienthal, 1993a; Kennedy, Lanham, Drexler, & Massey, 1995). This self-report measure contains a list of thirty separate symptoms. Participants are asked to indicate whether or not they are experiencing each symptom and, for some symptoms, the severity experienced on a scale from 0 (not at all) to 3 (severe). Analysis of the data produces an index of symptom experience on three subscales: nausea, oculomotor, and disorientation. The symptom profile produced has been used to compare the nauseogenicity of different stimuli (Kennedy et al., 1992).

The Short Symptoms Checklist (SSC) was designed specially for this study and comprises six symptoms (two taken from each of the SSQ subscales of nausea, oculomotor, and disorientation). Participants are asked to rate the severity of each symptom on a five-point scale (''not at all,'' ''slightly,'' ''moderately,'' ''definitely,'' and ''severely'') at five-minute intervals throughout the duration of VE participation and up to 45 minutes after immersion. Although not yet validated as an independent measure, the SSC provided a convenient profiling of symptoms experienced during VE immersion. These two methods were applied in all nine experiments resulting in a total participant sample of 148.

3.2 Physical Ergonomics Effects

Subjective reports of musculoskeletal discomfort were recorded using the technique of body mapping (Corlett, 1981). The body-mapping questionnaire required participants to indicate where they experienced discomfort during participation by indicating one or

Table I. *Summary of Experimental Program*

Expt. no.	Title	No. subs	Experimental design	Effects measured	Immersion duration
1	Investigation of general psychological effects	24	Measures pre- vs. postimmersion (single condition)	Simulator sickness, postural stability, psychomotor control, perceptual shifts, equipment fit, stress / arousal, enjoyment, usability, presence	20–30 mins
2	Initial examination of individual differences	20	Measures pre- vs. postimmersion (single condition)	Simulator sickness, concentration, enjoyment, usability, presence	20 mins
3	Physiological monitoring during VR immersion	4	VE vs. TV viewing (control) (within subjects)	Simulator sickness, neurological activity, neurological fatigue, cardiovascular change, biochemical change, stress / arousal, presence	50 mins
4	Changes in concentration after immersion in VR	16	Measures pre- vs. postimmersion (single condition)	Simulator sickness, neurological fatigue, concentration, enjoyment, usability, presence	50 mins
5	The effect of system lag on perceptual judgment	19	VE condition viewed at two processor speeds (within subjects)	Simulator sickness, perceptual judgment, stress / arousal	20 mins
6	Repeated exposures to a passive VE at different display speeds	12	3 VE conditions running at different rates of frames per second (within subjects)	Simulator sickness, neurological fatigue, cardiovascular change, stress / arousal, presence	20 mins
7	Extended immersion	4	VE vs. TV viewing (one participant wearing HMD with no display) (within subjects)	Simulator sickness, neurological fatigue, cardiovascular change, biochemical change, perceptual judgment, stress / arousal, presence	1–2 hrs
8	Postural stability before and after immersion in VR	40	Measures pre- vs. postimmersion (single condition)	Simulator sickness, postural stability, presence	20 mins
9	Ergonomics evaluation of three VR systems	9	4 VE conditions: 3HMD + 1 VDU (within subjects)	Simulator sickness, equipment fit, posture demands, usability, presence	20 mins

Table II. *Technical Specifications for Each Experiment*

		VR system characteristics					Visual display characteristics				
Expt.	Virtual environment VE	System	Processor power	Tracker delay[1]	FPS[2]	Input device	Visual display	IOD	FOV	Overlap	Weight
1	House I	Provision PV100VPX	VPX1	20 ms	2–15	3-D mouse	Dvisor	64 mm	105 × 41 deg.	46.4 deg.	2 kg
2	House I	Provision PV100VPX	VPX1	20 ms	2–15	3-D mouse	Dvisor	64 mm	105 × 41 deg.	46.4 deg.	2 kg
3	House II	Provision PV100VPX	VPX1	20 ms	2–25	3-D mouse	Dvisor	64 mm	105 × 41 deg.	46.4 deg.	2 kg
4	House II	Provision PV100VPX	VPX1	20 ms	2–25	3-D mouse	Dvisor	64 mm	105 × 41 deg.	46.4 deg.	2 kg
5	Heretic game	386 PC and Pentium 75	386/SX20 P75	4 ms	10–25	Keyboard	I-glasses	64 mm	30 × 23.6 deg.	100%	0.23 kg
6	Hospital corridors	Elysium	486/DX4 100 basic	20 ms	12, 25, 0–40[3]	V-flexor	Visette 2	64 mm	60 × 46.8 deg.	75%	0.68 kg
7	Gallery	Provision PV100VPX	VPX1	20 ms	5–25	3-D mouse	Dvisor	64 mm	105 × 41 deg.	46.4 deg.	2 kg
8	Zone hunter	Elysium	486/DX4 100 basic	20 ms	9–25	V-flexor	Visette 2	64 mm	60 × 46.8 deg.	75%	0.68 kg
9	Zone hunter + medical	Elysium	486/DX4 100 basic	20 ms	9–25	V-flexor	Visette 2	64 mm	60 × 46.8 deg.	75%	0.68 kg
	Gallery	Provision	VPX1	20 ms	5–25	3-D mouse	Dvisor	64 mm	105 × 41 deg.	46.4 deg.	2 kg
	Factory	Superscape	P100	4 ms	10–25	Joystick	I-glasses	60 mm	30 × 23.6 deg.	100%	0.23 kg
				N/A		Spacemouse	CRT monitor	N/A	N/A	N/A	N/A

[1]These figures are derived from manufacturers' documentation.

[2]A range of fps in any one immersion exposure is determined by user movement and interactivity within VE design parameters (e.g., the amount of information processed).

[3]In this experiment, users were exposed to different fps conditions: constant (held at 12 or 25 fps), acceleration (0–40 fps), or deceleration (40–0 fps).

more areas of the body on a simple diagram. They were then asked to describe the severity of that discomfort on a four-point rating scale (slight, moderate, severe, and very severe), and to state what aspects of VR/VE use they felt had contributed to this feeling of discomfort. These data were supported by questionnaire responses and post-immersion interviews.

3.3 Changes in Physiological State

Changes in physiological state were tracked by use of heart-rate monitoring at one-minute intervals using a Diascope. Changes in salivary cortisol composition were obtained by sampling every thirty minutes and treating the samples under HSE-approved, controlled conditions. (Early pilot work also assessed the value of EEG, critical flicker fusion frequency (CFFF) measures, and urine composition analysis.) The physiological data collection was designed principally to allow meaningful comparison with measures over time on the SSQ, SSC, and Stress Arousal Checklist (described later). Statistical tests of significance were possible for few of these data, because relatively small sample sizes were used due to the time, cost, and specialized personnel resources required. However, assessment of habituation and of consequences for extended participation was based on physiological measures as well as sickness symptoms.

3.4 Performance Changes

Performance changes were measured using tests applied in a test-retest experimental design. The participants were trained in performance of the tests before exposure to the VE, and post-performance levels were compared with baseline levels to measure any change in performance that had occurred due to immersion.

3.4.1 Postural Stability. A combination of static, dynamic, and posturographic postural stability tests were applied. Two static postures (''Tandem Romberg'' and ''Normal Stance'') were measured in terms of time that the posture could be held and the extent of hip sway over a thirty-second period using a sway magnetometer (Cobb & Nichols, 1999). Three dynamic tests were used: two walking on the floor with eyes (e.g., Kennedy, Fowlkes, & Lilienthal, 1993b; Hamilton, Kantor, & Megee, 1989) and navigation over a set, uneven path with eyes open (Cobb et al., 1995).

A Task Difficulty Scale (TDS) was administered after completion of these tasks. This is a short self-report measure in which participants are asked to describe how difficult they found a task on a five-point scale (''not at all difficult,'' ''slightly difficult,'' ''moderately difficult,'' ''very difficult,'' and ''extremely difficult''). In addition, participants completed the Postural Stability Questionnaire (PSQ) (Hamilton et al., 1989) before and after use.

3.4.2 Psychomotor Control. Several psychomotor tests were completed before and after VE participation to assess effects on performance that is typical of workplace tasks. Performance was measured by time and, where appropriate, error rates. (Some tasks were designed such that errors were reflected in the total time taken to complete the task.) Participants were also asked to complete the TDS after each test.

3.4.3 Visual Perception. Visual perception was measured using perception of reach-distance tasks. Participants were asked to stand in front of a table and hold their arm out so that their maximum reach distance could be measured. The participant then returned to a normal standing position and closed their eyes while eight markers were placed on the table, one of which was at their maximum reach. The participant then opened their eyes and were asked to judge which of the markers was at their maximum reach distance. The actual maximum reach distance of the participant, their perceived reach distance, and their confidence in this judgment were recorded.

3.4.4 Concentration. The Paced Auditory Serial Addition Task (PASAT) (Gronwall, 1977) was used to assess changes in the participants' levels of concentration before and after immersion. The number of correct responses provided a score (a higher score indicating a higher level of concentration). Participants also completed the TDS after the task.

3.5 Participant Experiences

The Stress Arousal Checklist (SACL) provides an instantaneous measure on two subscales—stress and arousal—after participants respond to a four-point adjectival response scale (Gotts & Cox, 1988). Enjoyment was measured using a ten-item adjectival response scale, consisting of five negative and five positive items. Presence was measured using a previously validated Presence Questionnaire (Singer & Witmer, 1996).

4 Experimental Findings

Table 3 lists the assessment methods used in the experiments. The experimental findings relating to participants' symptoms are summarized in Table 4.

4.1 Symptoms of Simulator Sickness

Figure 1 shows the SSQ profiles obtained in each experiment; the figure also includes levels of ''space sickness,'' ''sea sickness,'' and an average level recorded on a survey of seventeen simulators (''US Navy Fleet Average'') (Kennedy et al., 1992). Because the SSQ was applied throughout the experimental program and enables greatest comparability with other studies, results are reported at greater length than for other measures. It should be noted that the data for Experiment 7 are omitted from the graph due to low participant numbers. However, this experiment did yield some interesting results which are discussed in Section 4.1.2.

4.1.1 Participation of Twenty to Thirty Minutes. Experiment 1, 2, 5, 8, and 9 required participation of between twenty and thirty minutes. Experiments 1, 2, and 9 (div) all used the same system: the Di-

Table III. *Methods Used to Identify VR Effects*

	Method of assessment			
Effect	Self-report	Performance score	Physiological monitoring	Observation
Physical symptoms	• Simulator Sickness Questionnaire (SSQ) • Short Symptoms Checklist (SSC) • Body mapping • Ergonomics questionnaire		• Heart rate • EEG • CFFF	• Signs of physical discomfort
Performance changes				• Error in task completion • Observation of strategies used
• Postural control	• Task Difficulty Scale (TDS) • Postural stability questionnaire (PSQ)	• Static posture tests • Dynamic posture tests • Sway magnetometry		
• Motor control	• TDS	• Fine and gross movement tasks • Spiral tracing		
• Visual perception	• TDS	• Perception of reach distance • Perceptual judgment task		
• Concentration	• TDS	• Paced Auditory Serial Addition Task (PASAT)		
Consequences of immersion				
• Stress	• Stress / Arousal Checklist (SACL)		Biochemical change (urine and saliva): • Cortisol • Noradrenaline • Adrenaline Heart rate	Activity within VR Informal interviews postimmersion
• Enjoyment of VE	• Experience / opinions questionnaire			
• Presence in VE	• Presence questionnaire			

Table IV. *Physical Symptoms*

	Method of assessment		
Effect	Self-report	Physiological monitoring	Observation
Simulator sickness	Simulator Sickness Questionnaire (SSQ) ● 80% of all participants reported an increase in symptoms following immersion in a VE. For the majority of participants, the increase was mild, but noticeable, and subsided within 10 minutes after exiting the immersion. ● 5% of all participants experienced effects so severe that they could not complete the immersion. ● Different symptom profiles were obtained in individual experiments. Short Symptoms Checklist (SSC) ● Symptom onset usually occurred within 15 minutes of the immersion period. ● In immersion periods exceeding 30 minutes, symptom severity increased between 35–60 minutes. ● In repeated trials, symptoms levels were highest on first immersion and reduced to negligible levels on third immersions. This implies that participants habituated to the virtual experience after two immersions.	Heart Rate (HR) ● Varied in accordance with symptom reports. Participants with higher symptom severity also had higher HR. ● Distinctive trend of HR increase, followed by rapid fall and then slow recovery in participants who withdrew. ● Variability in HR greater during first immersion than subsequently. ● HR levels higher for VE than in control conditions of watching TV or wearing VR equipment without VE.	● Sweating at temples increased in those participants who reported sickness. ● Pallor observed in participants who withdrew. ● Participants experiencing sickness adopted a strategy of minimizing head movements.

Table IV. *(Continued)*

	Method of assessment		
Effect	Self-report	Physiological monitoring	Observation
Physical ergonomics effects	Equipment and Display Questionnaire (EDQ) A number of problem areas were identified: ● weight distribution of HMD ● design of handheld input device ● restriction of movement due to HMD connection cables ● visual disturbance from flicker, jitter, and lag of visual display Body Part Discomfort Rating ● Task activity produced specific sites of discomfort		● Participants used hand to support headset ● Prolonged static posture determined by VE task requirements and user interface design.

vision Provision VPX100. For Experiment 1 and 2, the profiles are similar, with reasonably high average scores on all three subscales. The scores are somewhat lower for Experiment 9, but this may be due to the low number of participants in this experimental condition. It may be the case that this small sample did not include any particularly susceptible participants, and this result highlights the need to examine in depth the role of individual susceptibility to VE sickness.

Experiment 5 compared two systems that were identical (I-Glasses) except for the processor speed of the computer (a 356 mHz PC versus a Pentium 75). The levels of oculomotor symptoms for these two conditions were higher than for the other immersions (which may be due to the I-Glasses being a low-end device with a small visual display of relatively low resolution), but they are also indicative of the domination of oculomotor symptoms in simulator or VE sickness in comparison with sea or space sickness (Kennedy et al., 1992). The participants reported higher levels of disorientation with the slower processor with its greater lag in the update rate of the display. Lag introduces an additional potential source of sensory conflict and may account for the higher incidence of reported disorientation. Whilst it is recognised that computer processing speeds are increasing as systems develop (and that both systems used in this particular experiment are now out of date), the findings are relevant for the selection of VR equipment that is suitable for workplace applications such as training or layout visualization. In Experiment 6, for example, VEs that deliberately accelerated and decelerated appeared to give rise to greater symptoms than those running at a steady frame rate.

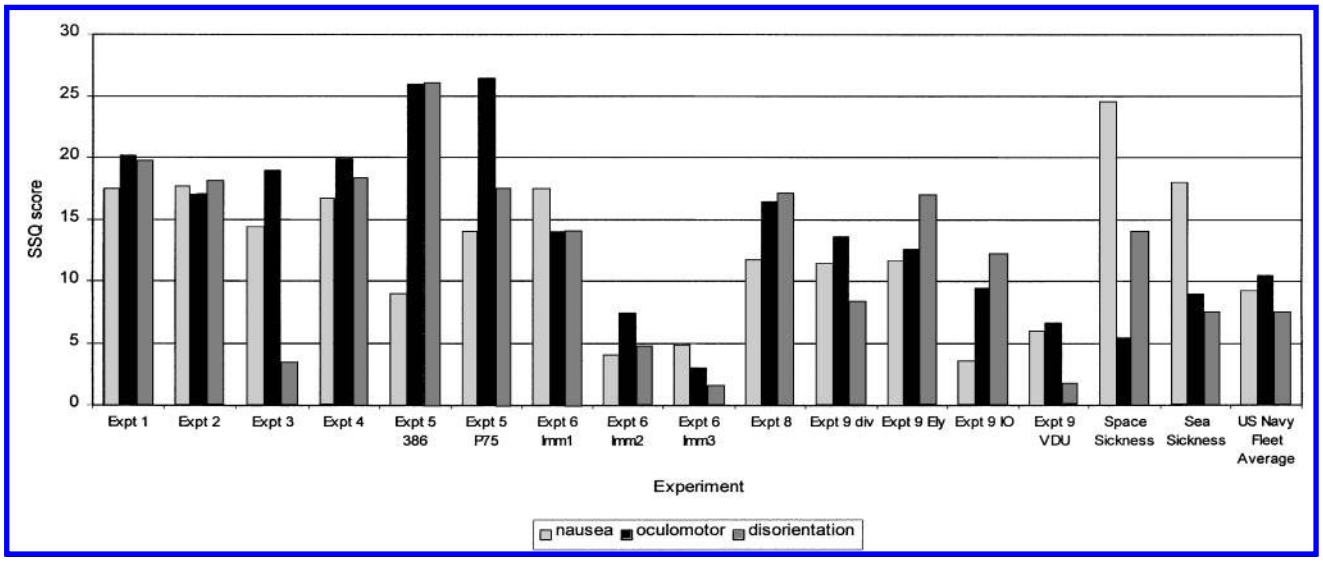

Figure 1. *Comparison of SSQ results from VIRART experiments, space sickness, sea sickness, and simulator sickness.*

The differences across system and VE configurations can be seen by looking at the results for Experiment 8 and 9. For Experiment 8, 9 (ely), and 9 (IO), there is no domination of oculomotor symptoms, and the general level of symptoms is lower. This may be due to the type of headset display (a steroscopic display). Finally, when compared with the symptom levels reported after the VDU condition, it can be seen that viewing VEs on a headset is more provoking of all types of assumption than viewing on a CRT monitor.

4.1.2 Habituation and Extended Participation.

The three conditions of Experiment 6 illustrate a habituation effect over three participations over three consecutive weeks, with decreasing levels of symptom expression from session 1 to 2 and from 2 to 3 (see also Regan & Ramsey, 1994). These results were particularly evident for the report of disorientation symptoms. The finding has important implications when considering the way in which VR / VE should be implemented in the workplace, suggesting that it may be appropriate to employ structured phased programs of VE participation.

Experiments 3 and 4 required participation in the VE for fifty minutes. The first thing to note is that there are no substantial differences between the sample mean of the general symptom levels for these and the shorter (twenty to thirty minutes) periods. This may be due to the fact that some participants felt so ill that they had to drop out of the experiment; therefore, their symptom reports cannot be included in these figures. However, the oculomotor symptoms still dominate. In Experiment 7, four subjects were asked to participate for up to two hours. All expressed increasing levels of symptoms up to one hour when two withdrew (with mean SSQ scores of $n = 67$, $o = 57$, $d = 82$). The other two reported subsiding symptoms after 75 minutes, returning to negligible based levels after two hours ($n = 5$, $o = 0$, $d = 4$), suggesting that these participants had adapted to the experimental conditions.

4.1.3 Individual Differences in Symptoms.

While the SSQ profiles are a useful indicator of differences between experimental conditions (i.e., differences between the VR systems or VEs), it is important to note that the mean scores presented in the graph are not a good indicator of individual differences. For example, as shown in Table 4, symptoms occurred during or after VE use for 80% of participants, indicating that the VR systems and VEs used in the experiments were indeed provocative stimuli. However, this also implies that 20% of participants did not experience any effects at all. Furthermore, for 75% of the participants, the symptoms

were mild and subsided soon after exit, but, for 5% of participants, the effects were so serious that the planned participation time could not be completed. This finding has important implications for the use of VEs in the workplace, as it indicates that a minority of potential users would be unlikely to gain any benefit from VE use and their work performance afterwards could be impaired.

Finally, it is important to note that participants' behavior changed if they were experiencing sickness symptoms (for instance, minimizing their head movements). This indicates that any sickness experienced will influence participant performance in the VE and thus the value of the experience to them or their employer—as well as being disturbing in itself.

4.2 Physical Ergonomics Effects

Two levels of ergonomics problem were identified: physical discomfort, such as pain in the head from wearing a heavy or ill-fitting headset, and problems that did not cause pain but were noticeable enough to distract the participant from the VE, such as feeling that their movement was restricted by the connecting cables. Any effects were generally mild, and not thought to remain for a long time after participation. The combinations of VR system, VE design, and individual user characteristics were particularly apparent in this family of effects. For example, the comfort of fit of an HMD was affected by the participant's head size and shape, and postural demands were affected by the requirements of the tasks in the VE; discomfort was reported in the shoulder region caused by one VE task that required participants to maintain static arm abduction, holding a 3-D mouse, for extended periods of time.

4.3 Physiological Measures

Physiological monitoring has largely been employed to track effects over time and especially to provide some comparison with self-reporting of symptoms. Heart rate and salivary cortisol levels both reflected well the increases in SSQ and SSC symptoms, especially throughout the longer participation of Experiment 7. Heart rate in all experiments typically went from approximately 75 to 90 before participation (elevated possibly due to anticipation) to approximately 90 to 115 during participation before returning to a resting rate of 60 to 75 after within thirty minutes of completion; in some cases, however, heart rate went as high as 150. Elevation in salivary cortisol between before participation and thirty minutes afterwards averaged $+12.4$ nmol/l (the stress of public speaking usually gives elevation of $+6$ nmol/l), with a peak at 19.5 nmol/l. Both heart rate and salivary cortisol level showed little change for control conditions. For the habituation Experiment 6, heart rate especially showed decreases across the three sessions, significant between sessions 2 and 3 ($p < 0.05$, $F = 8.85$).

4.4 Performance Changes

Findings from performance change tests are summarized in Table 5.

4.4.1 Postural Stability. Intra- and interparticipant variability produced high variance in results for postural stability, making statistical conclusions difficult to draw. However, the posturographic technique (sway magnetometry) was relatively successful, with consistent results providing evidence regarding the effects of VR/VE on postural stability, a small but consistent inducement of postural instability (20mm increase in sway over thirty seconds) which had subsided within ten minutes after exit. Although the effect was statistically significant, it must be considered in the context of the use of VR in the workplace. In other words, would a slight increase of sway that quickly subsides have any implications for user safety, even in simply walking from the place where they used VR to another location, or in performing any tasks after using VR? It may be the case that this small change detected by sensitive equipment may be an effect that is an indicator of other effects that are not detected by the dynamic tasks used. The association between the self-reported postural stability symptoms and the measures of simulator sickness indicates that a relationship does exist between the two types of effects. This may mean that one of the effects is a subset or

Table V. *Performance Changes*

Performance task	Self-report	Performance score	Observation
Postural stability	Postural Stability Questionnaire (PSQ) ● 24 / 40 participants reported symptoms of postural instability immediately post immersion. ● Strong correlations ($p < 0.01$) with all subscales of SSQ Task Difficulty Scale (TDS) ● No associations of dynamic test performance with perceived difficulty.	Static posture tests ● No significant differences due to intra- and intersubject variability Dynamic posture tests ● No significant differences in pre- vs postperformances. ● Significant practice effect noted on one test ($F = 10.64$; $p < 0.001$; $df = 44$). Sway magnetometry ● Significant increase in sway pre- vs. postimmersion ($t = 2.03$; $p < 0.05$; $df = 39$; two-tailed) which returned to preimmersion levels 10 minutes after exit from immersion ($t = 2.52$; $p < 0.02$; $df = 39$; two-tailed)	● Large variation in individual ability to perform static and dynamic tasks
Psychomotor control	Task Difficulty Scale (TDS) ● No associations of dynamic test performance with perceived difficulty.	Fine and gross movement tasks ● No significant differences in pre- vs postperformances. Spiral tracing ● No significant differences in pre- vs postperformances.	● Participants adopted strategies to enable them to complete tasks more quickly (indicating a possible masking of practice effect?)
Visual perception	Task Difficulty Scale (TDS) ● Participants reported task as being easier preimmersion or the same difficulty pre- and postimmersion	Perception of reach distance ● Significant underestimation of reach distance post immersion ($H = 0$; $N = 14$; $P < 0.001$; two-tailed). Perceptual judgment tasks ● No significant difference pre- vs. postimmersion	
Concentration	Task Difficulty Scale (TDS) ● Significant increase in reports of difficulty in completing task postimmersion ($H = 1$; $N = 10$; $p < 0.02$; two-tailed)	Paced Auditory Serial Addition Task (PASAT) ● No significant change in performance on concentration task postimmersion	● Participants adopted strategies to attempt to complete the task more accurately

product of the other, or that both effects are independently produced by the same underlying mechanism.

4.4.2 Psychomotor Control. No significant differences were found in pre- versus postperformance measures for fine and gross movement tasks. However, participants did report increased difficulty in performing the tasks after participation. Excluding the possible role of questionnaire response bias, this implies either that participants were experiencing a practice effect, with improvements in performance canceled out by a negative impact of VR use, or that a masking effect was occurring in which the participants were putting more effort into tasks completed postexposure to conceal any negative effects that had been experienced.

4.4.3 Visual Perception. Participants displayed a significant underestimation of reach distance postimmersion, but reported no change in perceived task difficulty or in the confidence in their performance accuracy. This might indicate that they were unaware of the change in their performance. There were no significant differences in perceptual judgement pre- versus postparticipation. It is interesting to note that the application of these tests in particular influenced—and was influenced by—other effects, illustrating the complex interactions that occur between effects and the tests themselves, and the problems faced when attempting to design strictly controlled experiments from which causative inferences can be made.

4.4.4 Concentration. Pre- and post-VE use showed no change in performance, but again increased difficulty was reported. This apparent contradiction may be explained as for psychomotor control tasks, although, because concentration is less likely to be subject to a classic practice effect, participants may have adopted different strategies to try and complete the task more successfully.

4.5 Participant Experiences

A number of general inferences may be made from the observations and measurement relating to the participants' experiences. (See Table 6.)

The fact that the physiological indices indicated increased stress effects adds to the evidence that the VEs used were provocative stimuli. The association between physiological stress measures and reports of sickness shows the links between different effects. Those participants experiencing stress as indicated by physiological measures were also observed to be more irritable and unwilling to complete the VE tasks.

It was apparent throughout the experimental program that the large majority of participants, whether they experienced negative effects or not, thoroughly enjoyed the novelty and opportunity for unique movement and interaction from participating in a VE. Correlation of the presence and enjoyment measures indicates that a sense of presence may enhance the experience of using a VE. If this is considered along with the negative association between sickness and presence (i.e., those who experienced a high level of symptoms experienced a lower level of presence), this emphasizes the fact that reducing the levels of symptoms experienced may have a positive impact on the overall experience of using the VE and on its utility in the workplace (Nichols, Haldane, & Wilson, submitted).

5 Implications of Findings

This study necessarily examined the effects of VE participation on a broad basis, which allowed the identification of both likely prevalence and importance (for employees and user companies) of the potential effects of VE participation. We have made progress in defining the types of research methods and measures that are required to address the broad question of what effects VR / VE has. However, one of the consequences of using multiple methods and measures is that some of the results and interpretations obtained from individual experiments cannot easily be generalized. Therefore, it is impossible at this stage to predict what set of outcomes may arise from an exposure to any particular VE, although some implications can be drawn for VR systems and VE design, and VR / VE use.

5.1 VR System

Responses to equipment and display assessment questionnaires indicate that the weight of the headset

Table VI. *User Experiences*

	Method of assessment		
Effect	Self-report	Physiological monitoring	Observation
Stress[4]	Stress / Arousal Checklist (SACL) ● Those participants who reported sickness either reported increased stress or gave more ''don't know'' responses. ● Participants not reporting symptoms did not report increased stress postimmersion, although some reported increased arousal.	Urine Analysis ● Increased adrenaline postimmersion ● No significant change in noradrenaline levels. ● Wide variation in cortisol levels postimmersion. Saliva Analysis ● Increased cortisol postimmersion (av. +12.4 nmol / l). ● Greater increases for those participants who experienced sickness Heart rate ● Participants with high stress scores had higher heart rates	Activity within VR ● Stressed participants showed signs of irritability and unwillingness to complete VE tasks
Enjoyment	Experience / opinions questionnaire ● General high level of enjoyment reported, despite any adverse effects experienced. ● Participants experiencing a greater sense of presence also reported a higher level of enjoyment	EEG Monitoring ● No changes in pre- vs. postimmersion levels Critical Flicker Fusion Frequency ● No significant differences in pre- vs. postimmersion levels	● Some participants asked if they could ''have another go.''
Presence	Experience / opinions questionnaire ● Association between low level of presence and high level of reported symptoms		
Difficulty	Experience / opinions questionnaire ● Association between high levels of difficulty and low level of presence		Activity within VR ● Participants got confused when required to press buttons on 3-D mouse to interact and move around Informal interviews postimmersion ● Reports of difficulty using handheld input devices ● Restricted field of view caused problems for task completion

[4]Due to small sample size, meaningful statistical tests could not be carried out.

may contribute to user discomfort. However, a lighter headset that is attached to the head over a smaller contact area could produce pain as a result of pressure points. Therefore, it is important that adjustment mechanisms and fit, in addition to weight and weight distribution, are considered in headset design.

The speed of the processing component of the VR system will influence the update speed of the visual display, and a slow processor may produce lag from update rates irrespective of any tracker lag. Limited investigations indicate some differences in disorientation and sickness with different update rates. A fairly obvious point for industrial use is that, when selecting VR system parameters for a given application, care should be taken to ensure that adequate processing speed is available to facilitate the user actions required within the VE.

The real conditions in which VR equipment is used may induce adverse symptoms or otherwise affect the virtual experience. For example, it is advisable to avoid the use of VR / VE in any hot or humid environments. It is well known that VR / VE use should avoid rooms with excess metal or magnetic components, because such settings could interfere with magnetic trackers and result in incorrect aspects of feedback. As well as interfering with performance, this phenomenon can confuse and disorient the user. Obviously, HMD use should not take place in areas where there are any hazardous objects or substances, as the participant is unable to see their real-world surroundings and may be at risk of injury. Care should also be taken to prevent users getting tangled up in the input / output cabling. Whilst seemingly trivial or obvious, these are all important considerations for real industrial application of VR / VE.

5.2 Virtual Environment Design

It was noted during the experiments that the physical behavior of the participants—required by the nature of the VE and goals of the task—often appeared either to induce discomfort or possibly was adapted to minimize any negative effects that might be experienced. Behavioral adaptations noted in these experiments were particularly the minimization of rotational head and body movements. In addition, participants commented that prolonged static postures (such as those that may occur when they had to hold their arm extended for a long time to enable interaction) contribute to postural discomfort. This can be avoided by a VE design that demands variations in posture (other than excessive rotations) while competing the tasks required.

It is likely that participants will expect virtual environments to maintain a relatively accurate representation of the real world, i.e., have ecological validity. Inaccurate representations could cause confusion and inappropriate actions and behaviors due to the lack of sufficient and correct visual cues and opportunities for interactions.

Although no formal evidence is available from the experiments, observation of use of different VEs indicates some relationship between perceived motion (or vection) and motion / simulator sickness, postural stability, and other effects. This conclusion has also been drawn by other authors (e.g., Kolasinski, 1996). Further work is planned to examine specific VE designs and the extent to which they induce effects.

5.3 Task and User Issues

The potential for multiple interactions and uncontrolled variables relating to the configurations of VR system, virtual environment design, user characteristics, and the task requirements used in the experiments makes it difficult to draw specific recommendations on guidance for VR / VE design and use. The identification of variability in participant experiences of symptoms and effects suggests that individual differences may have a stronger influence on participant experiences than VR / VE task configurations alone. As noted above, some participants developed behavior strategies such as minimizing head movements to reduce the experience of undesirable effects, and this was more noticeable in the experiments in which participants were exposed to repeated trials. This may indicate that the initial novelty of first-time use encourages full exploration of a virtual environment (e.g., participants tended to make many head movements to view all features within the VE), which is less evident on subsequent use of the same VE, when lower levels of symptoms were reported. (See Figure 1, Expt 6.) Until further work examining individual differ-

ences in susceptibility to, and experience of, side and after effects is completed, we must be cautious in our recommendations for VR / VE use.

In terms of general guidelines, we see no reason to deviate from those already provided by some commercial VR system suppliers: that viewing a virtual environment through an HMD should be limited to a maximum period of twenty minutes. Ideally, first experiences of VR / VE should be regarded as familiarization in which users can explore the VE for a limited time (perhaps less than ten minutes). If possible, users should be supported to try different strategies for exploration of the VE and consequent physical movement. All first-time participants should be monitored during, and for a short time after, their VR / VE use.

5.4 Theoretical Implications—Sensory Conflict Theory

It may be the case that VR / VE-induced sickness cannot be accounted for by any single one of the types of conflict suggested by Reason and Brand's 1975 model of sensory-conflict patterns. Instead, there may be a combination of Type II and Type III conflict. Type II conflict (visual information not backed up by corresponding vestibular information) occurs during any movement that is controlled by a handheld input device that does not provide any feedback to the vestibular system. In the use of VR systems, this usually occurs when the user experiences vection during forwards and backwards movement (or ascending and descending movement), which is primarily controlled by use of a 3-D mouse. In theory, users of VR are often able to move physically to a considerably greater degree than users of conventional flight or driving simulators, but, at the moment, technology limitations (e.g., cables or range of tracking devices) limit the amount of physical movement possible. So, although some vestibular information is provided, this is less than would be experienced in real-world movement. Type III conflict occurs when the head is moved (i.e., vestibular information is provided), but the expected visual information is not instantly provided to back up the changes in the vestibular system due to lags in the response of the visual display.

A VE participant will also receive input to the proprioceptive senses. A condition unique to VR / VE occurs when the information given by the proprioceptive senses—with respect to the position of the hand in relation to the body—may not tally with that given by the image of the virtual hand on the HMD. For example, a restricted field of view means that a participant has to be looking directly at their hand to see it, and the apparent reach distance may be different to the actual reach distance that is normally experienced. Therefore, it can be seen that, rather than the information from each of the sensory systems actually conflicting, it tends to be the case that there are shortcomings in the signals, so that the magnitude of each type of signal from the spatial senses is different to that which would normally be expected. This does still, however, result in the conflict between expectation and reality, which may produce symptoms of sickness.

6 Conclusions

The research program was organized with the principle aim of establishing if the implementation of VR / VE into industrial application will have health and safety consequences for participants. In order to do this, the program concentrated on establishing appropriate methods and measures and providing evidence for likely incidence and severity of a range of potential effects. Although some systematic manipulation of potential influencing factors was performed, this was not a priority at this stage; in any case, the rapid and continual development of VR technology can make all but systems-independent experiments very quickly redundant.

Findings from this study of civilian participants confirm those from the largely military-related studies that have been published. Symptoms and effects have been identified—some similar to those found with other types of simulators and in transportation—but the symptomology and possibly aetiology are sufficiently different to justify our coining a new term: virtual reality-induced symptoms and effects (VRISE). There is evidence for onset of symptoms of sickness for the large majority of participants, akin to simulator or motion sickness but

with some constituent experiences different from either of the other two better-established phenomena; for most, the symptoms were mild and short lived, but were for some so severe that they had to end their participation. Ergonomics assessments show considerable problems with the fit and discomfort of current-generation equipment, but no assessment of potential long-term health damage has been possible. Evidence for effects of VR use on subsequent task performance is equivocal, but increased difficulty was reported. Significant changes postexperience were found in postural instability, heart rate, and urine and salivary cortisol levels.

A number of further research questions associated with the effects of civilian (and especially industrial) use of VR / VE can be specified. These include:

- How do key variables of VR systems and VEs influence the more critical effects?
- Can we be more explicit about causal mechanisms?
- What is the time course of onset and recovery from effects?
- What are the critical differences that distinguish between individual user experiences?

Work is continuing on a metaanalysis of all outcomes by characteristics (including attitudes) of the participants, and on assessment via physiological indices. Further experiments will focus on VE design and consequent behavior and their influence on the production of VRISE in susceptible individuals.

A consequence of the multifactorial nature of VEs and VE participation is the difficulty at this time of providing a robust theoretical framework to understand the consequences of participation. Although frameworks have been proposed to understand some of the issues—such as sensory-conflict theory, or accommodation / convergence dissociation (Mon-Williams, Rushton, & Wann, in press)—we were unable in this program to develop any more-complete VE participation effects framework. The problems we found were confirmed within a NASA-sponsored workshop of 27 specialists in the field (including one of the current authors, J. R. Wilson), ''Aftereffects and Sense of Presence in Virtual Environments: Development of an R & D Agenda.'' This workshop emphasized the difficulty of undertaking fundamental research at this time and of producing an acceptable theoretical framework (Stanney et al., 1998).

One final point should be made here. Whilst we have undoubtedly found side- and aftereffects from VR / VE participation, including some potentially harmful for health and safety at work, these are not necessarily implicit in use of the technology. Many consequences are the function of particular system configurations, VE designs, and the circumstances of their use. Care in the design and set-up of these may significantly improve the quality of the VR / VE experience, reduce side effects, and aid the successful transfer of VR into industrial use. However, as we have found, individual differences are critical and research efforts should be directed towards identifying individuals who are susceptible to VRISE and the VR / VE configurations that provoke these effects.

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