ELSEVIER

Applied Ergonomics 30 (1999) 39–45

APPLIED ERGONOMICS

The nauseogenicity of two methods of navigating within a virtual environment

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Received 19 September 1996; accepted 6 August 1998

Abstract

This study compared the nauseogenicity of two different strategies for exploring virtual environments whilst wearing an immersive head-mounted display. In the first, the head was kept still and movement was achieved solely by manipulating a hand-control. In the second, the subject was free (and encouraged) to move his or her head when exploring the virtual world. Fourteen subjects completed both of the 20 min trials, three further subjects withdrew from the study after one trial. Subjects reported increases in adverse symptoms when using each strategy and, for the group as a whole, nausea increased steadily during each immersion period. However, significantly larger changes were reported when the head moved than when it was still, as predicted from sensory conflict theory.

Keywords: Nausea; Virtual simulation sickness; HMDs; Virtual reality; Computer games

1. Introduction

Over the last decade there has been a rapid increase in the accessibility of virtual environments. Computing power is increasing dramatically and, as costs decrease, we are approaching the stage where many families may have 'virtual reality' (VR) systems linked into home computers or the Internet. The use of this equipment is not confined to high-tech applications, such as training and maintenance, but also encompasses leisure applications including computer games. An integral part of some of these systems is the head mounted display (HMD), or head-coupled display, which provides the visual interface necessary for the feeling of 'immersion' in the virtual environment. Immersion, however, is not always free of problems, and an increasing number of studies have reported occurrences of what has been termed 'virtual simulation sickness' (VSS) (Howarth and Costello, 1996a). It has been suggested that this is an extension of the sickness experienced by people using flight and driving simulators, which itself appears to be an extension of motion sickness (Howarth and Costello, 1996b; Kennedy and Fowlkes, 1992; McCauley and Sharkey, 1992; Ward and Parkes, 1996; Stanney *et al*., 1999). Given the imminent proliferation of these systems it is important to understand the conditions under which VSS occurs along with the variety and relative importance of its multiple causal factors (Howarth, 1998). The study we performed investigated the nauseogenicity of two different ways of navigating within a virtual environment. On the basis of sensory conflict theory we predicted that each would produce feelings of malaise but in differing amounts.

Motion sickness or, more correctly, motion maladaptation syndrome, is a condition that occurs when people are exposed to real or apparent motion stimuli to which they are unfamiliar and hence unadapted (Benson, 1988). The term 'motion sickness' is a misnomer; motion maladaptation syndrome is merely an indication of intact vestibular function and, as such, should be regarded as the norm rather than the exception. It is believed that people have experienced motion sickness since the first use of transport (Reason and Brand, 1975) and indeed the first documentary evidence of this condition can be found in ancient Greek literature (nausea comes from the Greek word naus, meaning ship). The cardinal signs of motion sickness are nausea and vomiting, changes in pallor, and cold sweating (Reason and Brand, 1975; Benson, 1984,

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0003-6870/99/$ – see front matter
PII: S0003-6870(98)00041-6

1988). However, these signs are normally preceded by some (if not all) of the following physiological symptoms: stomach awareness, dizziness, bodily warmth, headache, sweating, increased or decreased salivation, drowsiness, and excess wind.

The classic theory explaining the causation of motion sickness symptoms is that of Neural Mismatch. The theory is based on work from over a century ago (e.g., Irwin, 1881; James, 1882; Pollack, 1893), but it has only gained wide acceptance since its promotion by Reason (1969, 1970, 1974, 1978), and Reason and Brand (1975). Neural mismatch generally occurs when there is a conflict between signals received from the visual system, the vestibular systems, and other gravireceptors. However, it can also happen when these signals differ from those *expected* by the central nervous system (CNS), and when there is conflict within the vestibular apparatus, i.e., between the semicircular canals and the otoliths. According to Benson (1984, 1988), motion stimuli are detected by the vestibular apparatus and receptors in the skin, joints and muscles, as well as by the visual system. The resultant signals are then compared with an internal model, which has been built up through experience of normal locomotor activity. Discrepancies result in a mismatch signal, and this can lead to feelings of malaise.

Simulator sickness in flight simulators was first reported in 1957 by Havron and Butler. A number of reviews have been published in this area, e.g. Griffin (1991) and Kolasinski (1995, 1996), who reported similar signs and symptoms to those reported for motion sickness. During the use of these simulators, neural mismatch occurs between the visual and vestibular systems, as, whilst the visual system signals that bodily movement is taking place, the vestibular system reports that the body is still. The problem is not confined to aircraft simulators, users of car simulators also suffer the same symptoms (Ward and Parkes, 1996).

Virtual simulation sickness appears to have multiple causative factors. The two that concern us here are the sensory conflict between the eyes and ears (McCauley and Sharkey, 1992), and the equipment update lag (Hettinger and Riccio, 1992; So and Griffin, 1995) both which are present in current VR systems. The potential for nausea can be demonstrated here by considering the two things that can happen to the eyes normally (in the real world) when the head changes position (Harris, 1994). The first option is that they can exhibit a reflex response movement (the vestibulo–ocular reflex) in the direction opposite to the head motion. This reflex movement acts to keep the eyes still whilst the head moves, so that the individual can remain looking in the same direction. The alternative option is that they can change their direction of gaze during the head movement, and look at something else. This ocular movement will generally be different in magnitude to the head movement, and so the position of the eyes in the head will change. In either case, the visual information and the vestibular information are consistent with each other.

For someone wearing an HMD, and viewing a virtual environment, whenever the head moves the visual stimulus differs from that of the real world. In all but the most expensive systems there is an appreciable delay between a head movement and the time when the new scene appears on the screen. This is known as an update lag (So and Griffin, 1995) and it leads to immediate sensory conflict because the vestibular system is recording movement of a given magnitude in a given direction which is different from the visual information that the user is receiving from the (moving) image on the screen. However, this is not the whole story. As an added complication, once the head movement is completed the vestibular system records that the head is still, but because the screen image is still changing the visual system records that movement is still taking place. Thus, the overall sensory conflict present when the head moves can be described as multi-factorial because of the different conflicts involved at different times during the head movement.

In the absence of head movement, sensory conflict can still occur if the virtual environment is navigated using a hand-control. The use of this control changes the visual scene, providing visual optic-flow information for the user which gives rise to a feeling of motion within the virtual environment. It has been predicted that when head-coupled displays provide rich scene content the user could suffer from vection-induced motion sickness (McCauley and Sharkey, 1992). Research from our own laboratory has led to the suggestion that movement alone is not the only consideration, but that the direction of movement is also important in determining the onset and amount of nausea experienced (Howarth, 1998).

We were interested in whether two navigation strategies, by head movement or by hand-control, differed in their nauseogenicity. In the first condition, subjects moved their head around to view the virtual world, whereas in the second the head remained still and the screen image was altered by the use of a hand-control. In the light of the theories of the causal factors of virtual simulation sickness, our first hypothesis was that there would be an increase in reports of symptoms during both conditions. Given that conflict was expected when the head moved, because of tracker lag, our second hypothesis was that head-control would be more nauseogenic than hand-control.

2. Method

The experiment involved each subject performing a single trial under each condition. In one, subjects changed their view of the world by moving their head. This is referred to here as the 'Head-Control' condition.

In the other, their view of the environment was altered by manipulation of a hand-held control, referred to here as the 'Hand-Control' condition. The order of conditions was balanced across subjects. Both sessions took place at around the same time of day to avoid possible circadian rhythm effects, and at least six days apart to attempt to minimise possible habituation or adaptation (Regan and Ramsey, 1994; Ramsey, 1996). The stimuli were identical for the two conditions, with the exception of any changes brought about by the control strategy.

2.1. Subjects

The 14 subjects who completed the experiment were healthy male ($n = 10$) and female ($n = 4$) volunteers in the age range 18–42 yr (mean 23.9 yr, S.D. 6.0), all of whom were staff or students from Loughborough University. All had intact vestibular function and were not receiving medication at the time. Only one subject had previous experience of VR systems. The Reason and Brand motion sickness susceptibility questionnaire mean (S.D.) score for the sample as a whole was 51.2 (30.9). This corresponded to a mean percentile score of 58%, indicating that the sample was very slightly more susceptible than the population at large to motion sickness. Subjects completed a medical questionnaire and consent form, and were made aware of the fact that they were free to withdraw at any time.

2.2. Sickness rating

At the end of each minute during immersion, subjects verbally rated themselves on the scale shown in Table 1.

For ethical reasons, the upper limit of the scale was restricted. The immersive session was stopped at sickness rating (SR) 4 or after 20 min, which ever was the sooner. Subjects also rated themselves periodically on this scale after immersion to assess recovery rates (Finch and Howarth, 1996) and to ensure that they had returned to their pre-immersion state before leaving the laboratory.

2.3. Equipment

The headset used was a Virtual i-glasses system, running from a 486 SX-33 with 8 Mb RAM. The Virtual i-glasses display is described by the manufacturers as consisting of two colour, 0.7 in liquid crystal display (LCD) screens which generate a $30^\circ \times 26^\circ$ field of view for each eye. The game played by the subjects was 'Heretic', in which subjects moved around a virtual environment shooting monsters. Stereopsis was absent as the same image was presented to both eyes. This was advantageous, in that accommodation-convergence variation was avoided (Wann *et al*, 1995).

The design of the headset is such that the inter-ocular distance (IOD) does not need to be adjusted. The virtual image was at a distance of 11 ft from the subject (according to the manufacturers), and subjects were allowed to wear any necessary optical correction. The head tracker sampled at 250 Hz and the overall update lag for the system was 550 ms[1]. The lag could have been decreased by using a more powerful PC, but the machine used was chosen as being representative of those likely to be found in the home environment at the time.

Forward and backward movements for both conditions were controlled by using a hand-held PC-Propad controller and subjects were not allowed to physically move backwards or forwards. Under the head-control condition all *directional* changes were made via head movements. Under the hand-control condition subjects were requested to keep their heads still and make directional changes via the game pad. Subjects were monitored to ensure compliance with these instructions.

2.4. Precautions

While immersed, subjects sat on a non-rotating stool. This was felt to be appropriate because of the possibility of subjects suffering from dizziness. Furthermore, although Regan and Price (1993a) stated that malaise ratings were similar for seated and standing subjects, a pilot study indicated that seated subjects who were forced to perform head movements, rather than whole-body rotations, reported more severe symptoms. It is worth noting here that, in discussing the genesis of virtual simulation sickness, Howarth (1998) distinguishes between dizziness which he suggests could be caused by movement in the real world, and nausea which could be caused by movement in the virtual world.

Although sessions were terminated at SR4, a motion-discomfort container was available at all times in case nausea continued to increase. Post-immersion, subjects remained seated until any feelings of dizziness disappeared, and individuals felt that they were capable of standing satisfactorily. Before leaving the laboratory, each subject was advised not to drive, cycle or operate heavy machinery for the rest of the working day. They

Table 1
Symptoms and ratings scale

Sickness Rating (SR)	Description
1	No symptoms
2	Any symptoms, but no nausea
3	Mild nausea
4	Moderate nausea (stop immersion)

[1] This was the measured time that elapsed, after the cessation of the HMD movement, before the image stabilised. During this period, intermediate images were generated.

were further advised to refrain, for the rest of the day, from any other activities where sudden disorientation could result in danger.

2.5. Data analysis

The data were analysed in two ways. First, the mean malaise scale rating for all 14 subjects was calculated for each condition at each time point. Although it is not strictly valid to average these data, as the malaise scale cannot be regarded as an interval level measure, this procedure was adopted to provide an overall impression of the changes which occurred over the task period, and to allow comparison with previously published data.

In order to examine the difference between the conditions statistically, a second procedure was adopted. For each subject the head-control scale rating was subtracted from the hand-control rating obtained at each equivalent time point. This gave one of three possible outcomes (head control greater (+), same rating (0), hand control greater (−)) on each occasion. When examining the complete sample of subjects, zero outcomes were ignored. The number of negative values was then subtracted from the number of positive values to give the sum total of subjects reporting a difference at each time point. For example, if six people had a higher rating for the head condition and one had a higher rating for the hand condition then the difference would be plus five. The statistical significance of these differences was calculated using a binomial test (Siegel, 1956).

3. Results

Three subjects initially recruited withdrew after the first session, as was their right. In each case, the trial had been of the head-control condition. Their data have not been included, leaving the sample of 14 subjects. One subject who withdrew continued to suffer extreme symptoms for a period of several hours post-immersion, including reported feelings of "car sickness", a phenomenon they had not experienced since childhood. Some subjects failed to recover completely within 10 min post-immersion and in some cases, symptoms persisted for a matter of hours following exposure. Reported symptoms varied from feelings of general discomfort to "severe hangover" and feeling "vacant".

The numbers of subjects reaching each sickness rating, by the end of each trial, are presented in Table 2. Subjects who reached SR4, and did not finish the trial, were rated as '4' for the remainder of the trial period. This is a conservative procedure, which may have reduced slightly the final average rating (particularly for the head-control condition).

Fig. 1 shows the mean rating, across subjects, at 1 min intervals for both conditions. Each function shows two portions, one increasing for the 20 min of immersion, and one decreasing once the HMD was removed. Subjects who reached SR4 before the 20 min was over, and stopped the immersion early, were also measured at 1 min intervals after the HMD was removed. Their data are included in the figure as if they had completed the full trial, and are averaged with those subjects who did. The ratings of *all* subjects at 1 min post-immersion is averaged, and the value is shown in Fig. 1 at a time of 21 min; the average rating at 2 min post-immersion is shown at a time of 22 min, and so on.

Table 2
Number of subjects out of 14 reaching each sickness rating stage before the 20 min cut off point

Sickness rating	Head-control	Hand-control
2	14/4 (100%)	10/14 (71.4%)
3	9/14 (64.3%)	3/14 (21.4%)
4	6/14 (42.9%)	1/14 (7.1%)

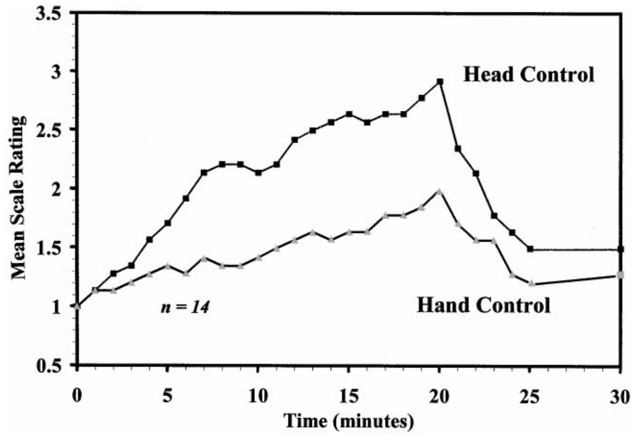

Fig. 1. The change in mean nausea rating over a 30 min period for the two conditions. Immersion ceased after 20 min.

The two conditions are clearly different in the time course of the increasing discomfort. In order to examine this difference statistically, Fig. 2 shows a comparison between the two conditions. The 'difference' value recorded is the number of subjects reporting more nausea in one condition than in the other, as described above. Clear statistical significance ($p = 0.002$) is reached between the conditions after only 8 min, with head-control being more nauseous than hand-control.

4. Discussion

The aim of this experiment was to investigate the nauseogenicity of two strategies for navigating within a virtual environment, by head movement or by hand control. Our first hypothesis, based upon sensory conflict

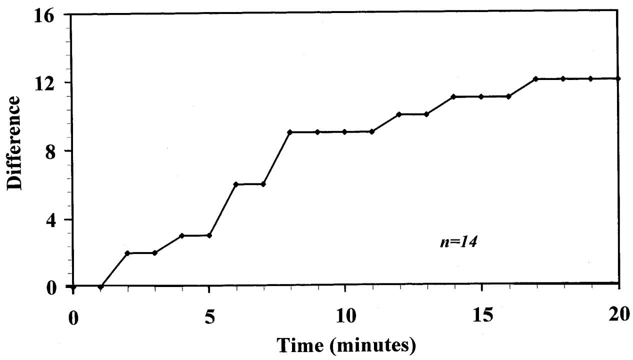

Fig. 2. The number of people reporting a difference in nausea in the two conditions, over the 20 min immersion period. A positive score indicates that subjects were experiencing more nausea under the head control condition than under the hand control condition.

theory, was that there would be an increase in reports of symptoms during both conditions. This clearly occurred. The results can be compared directly with those reported by Howarth and Costello (1996c) who examined nausea changes in subjects, wearing an HMD, who played chess for an hour. In their study, which used the same equipment and same rating scale as the current study, sensory conflict was present whenever subjects moved their head because the visual image did not change its location but the vestibular system would have signalled head movement. It is reasonable to suppose that their stationary stimulus was less nauseogenic than our dynamic stimulus, and a comparison of the results confirms this. None of their 20 subjects withdrew within the first 20 min, and at the end of this time period the mean nausea rating was 1.4, which is appreciably less than the 2.0 and 2.9 reported for the two conditions in the current experiment.

When the experimental task was completed, some subjects failed to show full recovery within the 10 min post-immersion recovery period under either condition. This is in accord with results from Regan and Price (1993a–c), as discussed by Regan (1995) and anecdotal reports of simulator sickness (e.g., Kennedy *et al*, 1987). The two conditions differed in their recovery characteristics: although in both cases there was a similar, large, initial fall in the average rating, at 10 min post immersion the average rating for the head-control condition was still appreciable higher than that for the hand-control. Perhaps more importantly, some subjects reported that symptoms recurred after they had reported being symptom-free. One reported that these symptoms lasted for up to 15 h. Clearly this has implications for persons required to drive or operate machinery after using the equipment.

The second hypothesis, that the head-control condition would be more nauseogenic than the hand control condition, can be accepted also. Direct comparison of the malaise ratings between the two conditions over the immersion period allows us to reject the null hypothesis with a confidence of $p < 0.001$ by the end of the trials. In addition, the times to reach each sickness rating were appreciably less under the head-control condition than under the hand-control condition. In the latter condition, four subjects failed to show any increase in nausea, and remained at SR1 (Table 1) whereas *all* subjects reported some nausea increase during the former. Furthermore, in the hand-control condition only three of the 14 subjects reached SR3, and only one reached SR4, compared with nine and six, respectively, for the head-control condition.

In the hand-control condition, the only conflict was between the vestibular apparatus, which indicated that no movement was occurring, and the visual system which indicated the occurrence of both linear and angular movement as the image on the screens moved. Although the visual field was greatly restricted, and the perception of movement through visual information alone is thought to depend predominantly upon peripheral vision, the conflict was still found to be nauseogenic. Ten out of the 14 subjects (71%) reported some increase on the malaise scale, although only one reported moderate nausea within the 20 min immersion period. These results are higher than those reported by Costello and Howarth (1996), who found that 13% of subjects reported a one-point increase in nausea (on a seven-point scale) whilst 6% reported a two-point increase. However, it must be noted that in the current study subjects were asked to rate nausea *during* the trial, whereas Costello and Howarth questioned subjects after immersion was over when some recovery was likely to have taken place. In the current study, once the immersion ceased the mean sickness rating for the head-control condition fell from 2.9 to 2.3 after 1 min and to 1.8 after 3 min. If the same rapid recovery was experienced by Costello and Howarth's subjects (who wore the same HMD, and played the same game, as our subjects) then their procedure would have underestimated the number of people experiencing nausea. Other studies using the same questionnaire approach may have suffered from the same problem and similarly underestimated the nausea.

When compared with previously published data, the results found when subjects were forced to move their heads are disturbing. *All* subjects reported increases in nausea, and six of the 14 (43%) subjects reported moderate nausea (SR4) within the 20 min immersion period. These figures are far higher than those detailed above from Costello and Howarth (1996); higher than those of Regan and Price (1993b), who reported that 70% of their subjects experienced some symptoms, but only 8% experienced moderate nausea or worse, and also higher than those of So (1994), who reported that approximately 90% of his subjects experienced some symptoms and 8% experienced moderate nausea.

Although our subject sample was very slightly more susceptible to motion sickness than the general population, this is unlikely to account for the discrepancy between our results and those reported previously, and cannot account for differences between conditions in our study.

During both conditions, all forward or backward movements were made via the gamepad hand-control. This is a requirement of all systems using this type of HMD because of the need for a data-carrying umbilical cord, which then limits forward and backward movement. Conflict occurs in both conditions when the visual inputs indicate movement, sometimes rapid, while the vestibular apparatus detects no movement. In addition, there are a number of differences between the two conditions that we can identify which may have led to the increased nauseogenicity of the head movement condition. The first involved rotational movement within the virtual world. During the hand-control condition, manipulation of the Propad controller led to movement of the 'world' relative to the subject, and because of this movement one might expect this condition to be the more nauseogenic. However, because of the system configuration, there was a mismatch between the head rotation and the subsequent screen image change, and a 120° rotation of the HMD resulted in a 360° turn in the virtual environment. Therefore, the virtual world turned three times faster than the real world, and when both were moving simultaneously the visual system would have indicated a rapid rotation while the vestibular system indicated a slower rotation of lesser magnitude. This was the normal mode of operation for this game, and so no attempt was made to alter it.

Update lags would have caused a mixture of conflicts. The first conflict was that as the head began to turn, the vestibular apparatus indicated movement while the visual inputs signalled that there was no change. The second is that during rotation the vestibular system would have detected regular angular acceleration and deceleration, while the visual information would have indicated jerky movement as the screen was updated on a sampled basis. The third was that as the head stopped the vestibular apparatus would have detected no movement, while the visual system would have indicated that the world was still moving — which would be interpreted to mean that the head was still moving. None of these conflicts were present under the hand-control condition, and it is reasonable to suppose they might each have contributed to the increased nausea reported for the head-control condition.

It remains to be seen which of these two differences, the movement mismatch or the multiple sensory conflicts caused by the update lag, led to the increased nausea in the head-control condition (or whether both contributed). It is possible, also, that there was actually an interaction between the two, and that if the update had been instantaneous the mismatch would have had greater impact. This is because, with the delay, there is no longer an instantaneous comparison between the sizes, and velocities, of the vestibular and visual changes occurring.

In summary, we have shown that the way in which a virtual environment is explored can affect the number of people experiencing nausea, and also the time of onset of nausea symptoms. The reasons for these changes have yet to be found definitively but the results of our study are consistent with expectations based on sensory conflict theory. Finally, we have noticed during other experiments that novice users will often change their navigation strategy with experience. They will, initially, explore the virtual environment by moving their head, but after a period of time they will change their behaviour and, instead, control the direction of their movement by manipulating their hand-control. This change in strategy may simply be convenient, however, our results suggest that it will have the effect of increasing the time of onset, and reducing the severity, of nausea.

Acknowledgements

This research was supported by the UK Health and Safety Executive, under Research Contract 3181/R53.133. We would like to acknowledge the helpful discussions held with Patrick J. Costello during this research, and the assistance of Jane Mee with the manuscript.

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