Visually Induced Motion Sickness

by
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A Doctoral Thesis

Submitted in partial fulfilment of the requirements
for the award of

Doctor of Philosophy of Loughborough University

March 2008

ABSTRACT

VISUALLY INDUCED MOTION SICKNESS

At times, people exposed to moving visual scenes may perceive themselves as moving even though they are, in fact, stationary. This sensation is sometimes experienced by people sitting in a railway carriage, in a station, when a neighbouring train slowly pulls away. Rather than sensing that the other train is leaving the station, they have the compelling feeling that their own train is moving in the opposite direction. This phenomenon, the feeling of moving brought about solely by a change in the visual scene, is called vection.

Sustained exposure to moving visual scenes may not only produce vection, but can also provoke signs and symptoms of motion sickness such as dizziness, sweating, stomach awareness, and nausea and these adverse effects are now generally termed "visually induced motion sickness" (VIMS). VIMS is frequently reported in a variety of simulated or virtual environments such as flight and driving simulators, as well as in other contexts, such as at the cinema. It not only constitutes a nuisance to the user of these technologies, but also limits the usability of these technologies.

Unlike other forms of motion sickness, such as seasickness, little is known about what conditions, or what aspects of moving visual scenes, are particularly provocative. Furthermore, research conducted thus far has generally investigated rotational motion patterns that are not representative of motion typically encountered in the real world. As a consequence, the work presented here has investigated the interrelationship between visual stimulus characteristics, VIMS, and vection during simulated forward and backward self-motion (i.e. along the fore-and-aft axis).

In the first study, individuals were exposed to moving visual scenes that induced an illusion of motion in the fore-and-aft axis. These were presented either at a constant speed, or at a sinusoidally varying speed. Although varying the speed was expected to lead to higher levels of VIMS, this was not observed. The absence of an increased level of VIMS was hypothesised to be a consequence of the particular frequency employed (0.025 Hz). The frequency dependence of VIMS was then tested in a series of experiments. Noting that amplitude and acceleration covaried with frequency, it was found that within the range 0.025 - 1.6 Hz, VIMS peaked at 0.2 Hz. Using motion profiles with varying amplitude and acceleration, studies employing angular motion stimulation, on the other hand, had previously shown a peak in VIMS to occur at a frequency of approximately 0.06 Hz. This suggests that results obtained with angular motion stimulation cannot be extrapolated to scenarios involving linear motion stimulation in the fore-and-aft axis.

The studies thus far isolated the effect of stimulus characteristics by preventing eye movements from occurring by means of fixation. A further study was conducted with the express purpose of investigating the effect of gaze shifting. It was found that the level of VIMS significantly increased with fixation away

from the focus of expansion of a radial display. This suggests that the visual stimulus interacts differently with different portions of the retina.

Real-world motion scenarios generally entail motion along different axes simultaneously. Most studies into VIMS have been restricted to single-axis motion and, although VIMS is assumed to increase with more complex motion scenarios, little is known about how VIMS changes with increasing complexity. Comparing single- versus dual-axis motion, it was unexpectedly found that dual-axis motion did not lead to higher levels of VIMS, challenging the generally held assumption that VIMS is proportional to the degree of sensory conflict.

The feasibility of predicting the incidence of VIMS based on an individual's motion sickness history as assessed by the revised Motion Sickness Susceptibility Questionnaire (MSSQ) was finally explored. Correlation coefficients were comparable to those observed with true motion suggestive of a common underlying mechanism between different forms of motion sickness. For the prediction of individual behaviour, the MSSQ was found to be of limited value in its current form.

A general finding was that vection consistently preceded the occurrence of VIMS, in line with the idea that vection is a necessary condition for VIMS to occur. This implies that future displays optimising the simulation of self-motion are likely to result in higher levels of VIMS. In addition, the findings that frequency, gaze direction, and multi-axis motion affected VIMS differently with simulated motion in the fore-and-aft axis as compared to angular motion profiles, indicate that angular motion commonly used to study VIMS may be of limited value.

Acknowledgements

Considering the nature of the work presented in this thesis, my first thanks must go to all those volunteers willing to participate in my studies.

I would further like to thank the following people for their contributions toward this work:

Many thanks must go to Dr Peter Howarth, my supervisor. His continued support, sharp mind, and pub meetings have been invaluable throughout the years of this PhD.

Dr Simon Hodder for the many enjoyable hours discussing matters of various kinds as well as his moral support throughout.

I am also very grateful to Professor Kazuhiko Ukai who made it possible for me to work at his lab at Waseda University in Tokyo. Many thanks also to all the members of his lab who have been very helpful and made it a very enjoyable experience. Special thanks must go to Kohei Meguro and Masahito Torii.

I would also like to thanks Dr Ian Tucker for proofreading. Cheers!

Technical support was crucial to this research and thanks must go to John Pilkington and Dave Harris. I am particularly grateful to Dr Luca Notini for the stimuli development and Dr Andrew Rimell for the data acquisition software.

I would like to thank my examiners, Professor Richard So, Professor Alastair Gale, and Dr Neil Mansfield, for reading the book in the first place, as well as their suggestions, ideas, and interesting discussions.

Finally, sincere thanks must go to my parents, Harry and Helga Diels for all their help, support and encouragement throughout my education, culminating in this book.

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Introduction

Moving visual scenes can sometimes give rise to an illusory perception of self-motion. This phenomenon is known as 'vection' (Tschermak, 1931). In everyday life, vection may be experienced when sitting in a railway carriage in a station and a neighbouring train slowly pulls away. Rather than seeing the other train leave the station, one may have a compelling feeling that one's own train is moving in the opposite direction. The motion seen gives rise to a mistaken feeling of self-motion.

Misinterpretation of the image movement across the observer's retina may perhaps not be too surprising when one considers that under most natural conditions, movement of a large, distant proportion of our surroundings is very rare. Natural surroundings or scenes are normally Earth-stationary. Hence, the presence of relative motion between ourselves and large parts of our surroundings tends to be attributed to self-motion rather than movement of the surroundings (Dichgans & Brandt, 1978).

The powerful effect of visual stimulation has long been recognised and exploited in many fairground devices. In the late 19th century, for example, the "Haunted Swing" was a popular fairground device whereby fairgoers were seated in a stationary gondola inside a large furnished room rotating around stationary observers (see figure below). Following his visit to the Midwinter Fair in San Francisco, Wood (1895) engagingly described his experiences thus:

> *We took our seats and the swing was put in motion, the arc gradually increasing in amplitude until each oscillation carried us apparently into the upper corners of the room. Each vibration of the swing caused those peculiar 'empty' sensations within which one feels in an elevator; and as we rushed backwards towards the top of the room there was a distinct feeling of 'leaning forward,' if I can describe it – such as one always experiences in a backward swing, and an involuntary clutching at the seats to keep from being pitched out. We were then told to hold tightly as the swing was going clear over, and, sure enough, so it did... (p. 272).*

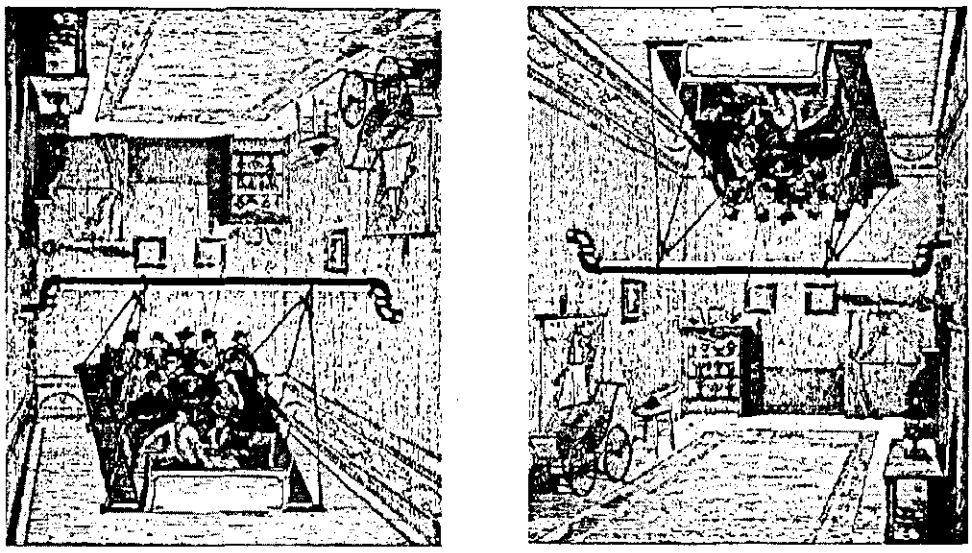


Illustration of a haunted swing (Hopkins, 1898). Left: true position of the swing. Right: illusion produced by the haunted swing.

In essence, the haunted swing can be regarded as a precursor of modern simulators and Virtual Reality (VR) systems. Physically rotating rooms have been replaced by interactive computer-generated environments that are presented via advanced display systems such as head-mounted displays. The underlying principle has however remained unchanged and optical simulations of self-motion in these systems may also give rise to an illusory perception of self-motion.

Sustained exposure to such visual stimuli may however reduce their entertainment value. In his account of the haunted swing, Wood (1895) noted that "*Many persons were actually made sick by the illusion. I have met a number of gentlemen who said that they could scarcely walk out of the building from dizziness and nausea*" (pp. 277-278). Similarly, users of simulators and other VR technologies are widely reported to experience adverse symptoms.

Many decades after Wood's observations, the occurrence of negative side effects following exposure to so-called optokinetic stimuli has in fact become a scientific field of research in its own right. The constellation of signs and symptoms has been variously named 'simulator sickness', 'cybersickness', 'virtual simulation sickness' and these have been partly attributed to 'vection induced sickness', or 'visually induced motion sickness' which forms the topic of this thesis.

Simulators and Virtual Reality (VR) technology are increasingly used for research, training, design evaluation, but also entertainment (Stanney, 2002). The ability to immerse users in interactive simulated or Virtual Environments (VE) provides some distinct advantages in that it allows users to be exposed to scenarios that in real-life would be too dangerous, costly, physically impossible, or simply non-existent. However, the ultimate acceptability and usability of these technologies is limited by the occurrence of Visually Induced Motion Sickness or 'VIMS' (Lawson et al., 2002; Stanney et al., 1998; Wilson, 1996). This has perhaps most literarily been expressed by Biocca (1992) who stated that VIMS may remain a 'snake' lingering in the underbrush of virtual worlds threatening the widespread diffusion of this technology.

VIMS not only constitutes a considerable nuisance to the user, but also interferes with the intended goals for which these technologies are used (Kennedy et al., 1990). In the context of training, VIMS may hinder the learning process within a VE; prevent individuals from participating in the training; limit the length of time for which training can occur; and may lead to negative transfer of training, i.e. users may adopt behaviours to avoid symptoms in the VE which may not be similar or appropriate in situations outside the VE, such as restricting the amount of head movements during flight simulator training. VIMS may further compromise the usability of these technologies as a research tool in that it may lead to incomplete or invalid data. Obviously, this provides a strong practical motivation to gain a better understanding of the underlying mechanisms.

In many ways, VIMS resembles the motion sickness classically experienced in for example ships, cars, and aeroplane. Users experience signs and symptoms such as nausea, sweating, headaches, increased salivation, pallor, drowsiness, dizziness, stomach awareness, nausea and vomiting (Lawson et al., 2002). Other additional symptoms that are unrelated to motion sickness have also been reported for people immersed in a VE including general visual discomfort and eyestrain (Mon-Williams et al., 1993; Howarth & Costello, 1996b). Furthermore, while studies in true motion sickness indicate that once a provocative stimulus has ceased symptoms generally disperse within ten minutes (Reason & Brand, 1975), symptoms experienced in simulators and VR

systems have been reported for long periods after exposure, ranging from hours till even days (Howarth & Finch, 1999; Kennedy et al., 1990; Regan & Ramsey, 1994; Wertheim, 1999). Repeated exposure to a provocative environment does however render most individuals insusceptible to a previous provocative motion environment. This habituation has been shown to occur with regard to both VE symptoms (Clemes & Howarth, 2003; Regan, 1995) and true motion sickness (Reason & Brand, 1975). Estimates of incidence of VE symptoms vary widely and can occur from almost never (< 5%) to almost always (> 95%) (Howarth & Costello, 1997; Howarth & Finch, 1999; Kennedy et al., 1997; Lawson et al., 2002; Regan & Price, 1994; Regan, 1995; Stanney et al., 1998; Wilson, 1997). This large variability may not be surprising considering that the symptoms that arise within a VE are the result of a complex interaction between factors related to the individual, task, and system characteristics (Kolasinski, 1995). Consequently, VE symptoms has been described as not only being polysymptomatic but also polygenic (Howarth & Costello, 1996; Kennedy & Fowlkes, 1992; Kolasinski, 1995; Nichols & Patel, 2002).

Despite the many contributing factors, it is often accepted that the root cause of both VIMS and true motion sickness is the presence of sensory rearrangements, i.e. altered patterns of sensory signals within the human CNS that are not expected based upon previous experience (Oman, 1982; Reason & Brand, 1975). Our perception of self-motion is achieved by integrating the information from the different sensory systems involved in the computation of self-motion, most importantly the vestibular system, visual system, and somatosensory system (Howard, 1982). Under normal conditions, the information provided by these sensory systems is concordant. However, there are many situations where the information is discordant, and where an adequate sense of self-motion is not evident. For instance, when we are inside a ship compartment, our vestibular system registers the motion of the ship, whereas our eyes detect a stable environment. Conversely, in a fixed-base driving simulator or wide screen cinema (e.g. IMAX), changes in the visual world may lead to the feeling of self-motion. This information does however not correspond to that provided by the vestibular and somatosensory system, which signal that the body is stationary. According to the sensory conflict theory

(Reason & Brand, 1975), it is these kind of sensory rearrangements that underlie the generation of motion sickness. Reason and Brand summarised their theory as follows:

> ...all situations which provoke motion sickness are characterized by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular system and the nonvestibular proprioceptors are at variance not only with one another, but also with what is expected on the basis of past experience... (Reason & Brand, 1975, p. 105)

Although the sensory conflict theory provides a useful framework to guide research into motion sickness, an important limitation of the theory in its current form is its qualitative nature and inability to predict the extent of symptoms or how they depend on the magnitude, type or duration of motion (Denise et al., 1996; Griffin, 1990; Kolasinski, 1995; McCauley, 1984; Riccio & Stoffregen, 1991).

In order to be able to predict the incidence and severity of VIMS, a sensible approach would be to identify contributing factors. More specifically, considering VIMS to be visually induced, a logical first step would be the identification of visual stimulus characteristics that are most conducive to VIMS. This has already been shown to be a successful approach with regard to seasickness. Systematic studies into the relationship between motion profiles aboard ships and subsequent laboratory studies have shown oscillating motion along the vertical axis at around 0.2 Hz to be the main cause of seasickness (Lawther & Griffin, 1986, 1988; McCauley et al., 1976; O'Hanlon & McCauley, 1974). This has subsequently led to the development of a Motion Sickness Dose Value (MSDV) for predicting seasickness based on the vertical motion of vessels (BSI, 1987). This information has been used successfully in the design process, which has led to the construction of transport systems that are less provocative of motion sickness.

Following the same rationale, identification of visual stimulus characteristics that are most conducive to VIMS may provide valuable information. First, it may create a better understanding of the aetiology of VIMS, and secondly, identification of dominant axes and motion profiles allows for the prediction of

VIMS. Ultimately, it may be possible to develop a 'Cyber Sickness Dose Value' as envisioned by So and colleagues (Ji, 2004; So, 1999; So et al., 2001).

Hitherto, there is however a dearth of knowledge regarding the effect of visual stimulus characteristics, which undoubtedly form the key element in the aetiology of VE symptoms. Previous work has identified a plethora of factors that contribute to the occurrence of VE symptoms (for review see Kolasinski, 1995). However, these studies have predominantly focussed on system characteristics (e.g. field-of-view, update lags, display characteristics, method of navigation) and individual characteristics (e.g. age gender, field-(in)dependence, posture) (see also Lo & So, 2001). Almost 10 years ago, the importance of investigating the relationship between visual stimulus characteristics and VIMS had already been acknowledged by leading researchers in the field. Besides the need for standardisation of measures, the identification and prioritisation of sensorimotor discordances (i.e. sensory rearrangements) that drive VIMS was denoted as the most critical research issue (Stanney et al., 1998).

A closely related issue concerns the role of vection in the generation of VIMS. Based on observations that only those individuals who report vection also report VIMS has led to the suggestion that vection is a prerequisite for VIMS to occur (Hettinger & Riccio, 1992). Furthermore, findings that conditions leading to stronger feelings of vection on average also lead to higher levels of VIMS has led to the contention that the degree of vection reflects the degree of sensory conflict (Hettinger et al., 1990; Hu et al., 1997). However, others implied vection to be merely an epiphenomenon; vection and VIMS may be separate phenomena that often co-occur but share no causative relationship (e.g. Webb & Griffin, 2002). The observation that simple visual stimuli induce stronger feelings of vection but less VIMS compared to complex visual stimuli (Andre et al., 1996; Bubka & Bonato, 2003) further indicates that the relationship between vection and VIMS may not be as obvious as often assumed. The role of vection becomes particularly relevant in the context of 'presence' which can be defined as the subjective experience of being in one place or environment even when one is physically located in another (Witmer & Singer, 1998). Since presence has been related to the efficacy and enjoyment of virtual environments and

simulators (for review see Stanney et al., 1998) considerable effort continues to be invested in optimising the perception of self-motion (e.g. POEMS, 2001) which, in turn, has been considered to be an important element in the sense of presence (Hettinger, 2002). The benefits of a compelling sense of self-motion may however be dramatically offset by the occurrence of VIMS (Hettinger & Riccio, 1992; Hettinger, 2002; Stanney et al., 1998).

Research aims

The main objective of the work presented in this thesis is to explore the relationship between visual stimulus characteristics and VIMS. Although inherently compromised by the need for rigid experimental control, ecological validity forms the starting point. Much of the previous work on self-motion perception and VIMS has been limited to rotation about a vertical axis. Notwithstanding its significant contributions, it should be recognised that rotation has only a limited role in the normal locomotion of the human observer (Gibson, 1950). The principal motion components that occur during normal locomotion of a person are likely to be translations and, more specifically, translation along the line of sight in the forward direction. Accordingly, the current work focuses on VIMS during linear motion.

An additional aim is to integrate the study of self-motion with that of motion sickness. Despite the vast literature on self-motion perception, motion sickness has never been an integral part of this research. This may perhaps not come as a surprise considering that the short exposure durations typically employed in these studies are generally not conducive to VIMS. In studies on VIMS, on the other hand, vection is often assumed to have occurred but rarely assessed. If so, it is mainly of qualitative nature whereby the temporal correspondence between vection and VIMS is often neglected. Characterisation of VIMS and vection in terms of magnitude and time-course is expected to shed some light on the controversy regarding the relationship between the two.

Thesis structure

VIMS can be considered the outcome of perception gone wrong. The brain mistakenly, although understandably, attributes visual motion to movement of itself, or the observer's body for that matter. Considering the pivotal role of self-motion perception, the review of the literature presented in chapter 1 starts off with a discussion on the senses involved in self-motion perception. Chapter 2 gives an overview of the experimental setup and methods that were used to assess VIMS and vection. The core of the thesis consists of the experimental work and is described in chapters 3 to 7. In the final chapter, the findings from the previous chapters are briefly summarised and discussed in the context of the aims underlying this thesis.

C_1
Literature Review

1.1 Summary

VIMS can be regarded as a normal response to an abnormal environment in which the relationship between different self-motion cues has been altered. Hence, in order to understand the aetiology of VIMS, a basic knowledge of the different sensory systems involved in the computation of self-motion is required and will be provided first. A number of theories on motion sickness have been put forward which will be briefly discussed with reference to VIMS in particular. The most widely accepted theory of motion sickness, the sensory conflict theory, will subsequently be used as a framework to discuss previous studies into VIMS. This is followed by an overview of specific studies that addressed the relationship between visual stimulus characteristics and VIMS. The chapter will close with a discussion on previous studies into the effect of visual stimulus characteristics.

1.2 Perception of self-motion

During active or passive displacement of the body, the CNS is supplied with visual, vestibular, somatosensory, and auditory signals, as well as efferent copies of motor commands (Berthoz, 2000). From these multiple sources, a coherent perception of self-motion in space is built in relation with the control of body movements. Under normal circumstances, these sensorimotor signals provide coherent information that allows adequate perception and control of self-motion. The accuracy of this multisensory integration process is however limited by physiological characteristics of the biological motion sensors, which in certain situations yield partial or ambiguous information. For example, the vestibular system responds to accelerations only and is unable to signal constant velocity motion. The motion signals provided by the visual system are inherently ambiguous and may correspond to a displacement of the observer, motion of the visual environment, or reflex movements of the eye and head. These examples show that motion sensors do not directly signal the real motion of the body. Efficient perception of self-motion thus requires multisensory integration at the central nervous system level(Borah et al., 1988; Merfeld et al., 1999; Mergner & Rosemeier, 1998; Reymond et al., 2002; Zacharias & Young, 1981). The different sensory systems involved in the perception of self-motion are discussed in the following section.

1.2.1 Vestibular information

The vestibular system, shown in figure 1.1, is a small structure that exists in the bony labyrinth of the inner ear. It provides information about the movement and orientation of the body in space, assists in the maintenance of an upright posture, and controls eye position as we move our heads while viewing various stimuli (Howard, 1986a). It comprises the non-acoustic part of the inner ear, which consists of three semicircular canals for detecting angular acceleration in 3D and the otolith organs consisting of the utricle and saccule, which detect linear acceleration in 3D and gravitation (see figure 1.2 for kinematics nomenclature). The VIIIth nerve is the efferent pathway for vestibular signals,

transmitting head movement and head positioning data to various centres in the brain with the main relay station being the vestibular nuclei (Howard, 1986a).

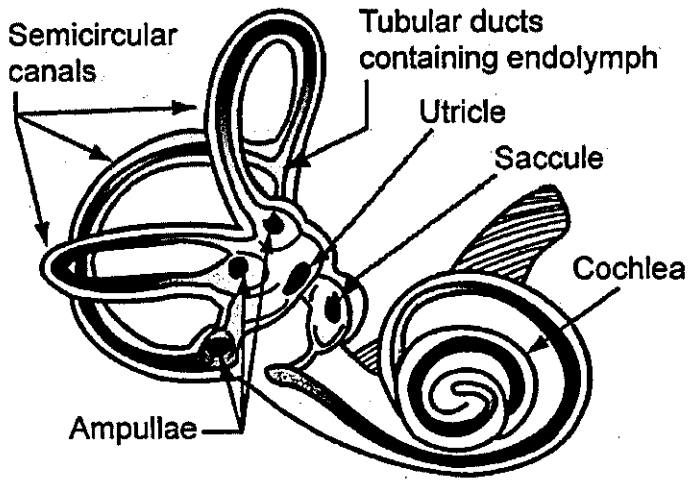


Fig. 1.1 The vestibular system – semicircular canals and otolith organs.

Semicircular canals

The three semicircular canals lie in different orthogonal planes, corresponding to each of the three dimensions in which human movement can take place. Each canal is filled with a fluid called endolymph, and is prevented from passing through the ampula (a widened section of each semicircular canal) by the cupula. The cupula is a thin flap that stretches across the ampula and acts as a barrier to endolymph flow. When the head is rotated, the force exerted by the inertia of the fluid acts against the cupula of those semicircular canals that are in the plane of motion, causing it to deflect. This deflection causes a displacement of tiny hair cells, located at the base of the cupula in the ampula, which either increases or decreases the discharge rate of the nerve cells, depending on the direction of movement. If the rotation continues, the endolymph catches up with the movement of the canal and the cupula is returned to its resting position with the discharge of the nerve fibres returning to their former rate. This has important implications for the detection of self-motion. As a consequence of the inertia of the endolymph within the canals, sustained acceleration and constant velocity motion cannot be sensed by the vestibular system. Hence, the effective stimulus is acceleration rather than steady

movement. Due to these mechanic properties of the vestibular system, non-veridical perceptions of self-motion can occur if rotation is suddenly brought to a halt for example. Whereas the canals immediately stop their rotation, the endolymph does not and so the cupula is bent in the other direction leading to an illusory perception of motion in the opposite direction (Howard, 1986a).

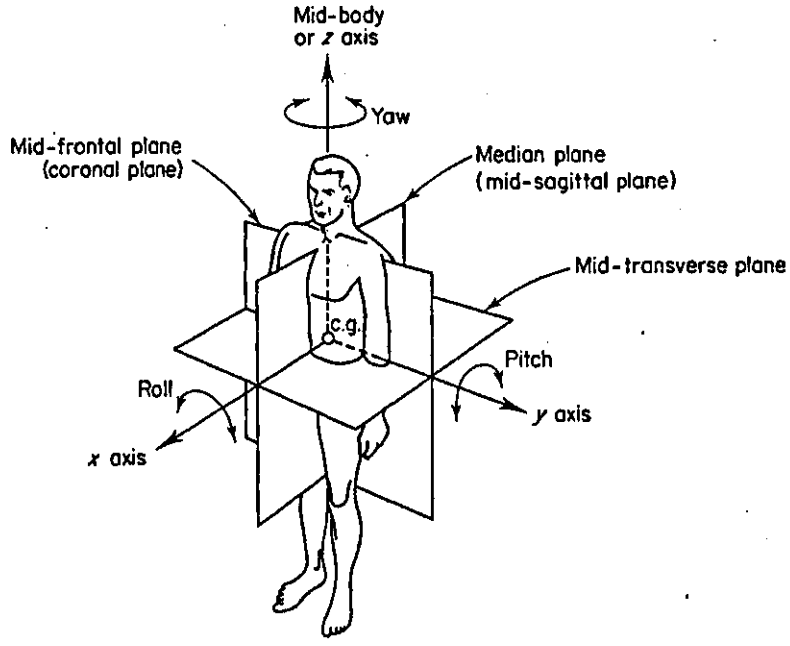


Fig. 1.2 Axes and planes of reference for the human body. The three principal axes intersect at the centre of gravity of the body. The arrowhead on each axis points in the positive direction along that axis (Hixson et al., 1966).

The bending of the hairs generates neural responses that are transmitted to the vestibular nuclei receiving areas of the brain via the VIIIth nerve and then to the VIIIth nerve nucleus. From the VIIIth nerve nucleus, there are various connections to the cerebellum and other nerve nuclei, including those involved in the control of eye movements. Each pair of eye muscles receives fibres from a different semicircular canal. Muscles that move the eye in a certain direction are controlled by nerve fibres that originate in one of the semicircular canals that respond to acceleration in that plane. Accelerations in a particular direction causes compensatory eye movements in the opposite direction that allow the eyes to remain fixed on an object even though the head is turning in various directions. This is called the vestibulo-ocular reflex (VOR).

Otolith organs

The perception of dynamic changes in linear acceleration and static head position, such as head tilt, originates from sensory organs (maculae) located within the utricle and saccule, more commonly known as the otoliths (Howard, 1986a). The maculae consist of flat gelatinous masses (otolithic membrane) covered with minute crystals (otoliths or statoconia) connected to an area of the utricle and saccule by cells, including hair cells. Translational force causes the mass to exert a shear force, thereby dragging the hair cells from side to side to provide the perception of motion. The utricle's macula is located in the horizontal plane so as to be sensitive primarily to horizontal accelerations, while the saccule's macula is positioned vertically to be maximally sensitive to vertically directed linear accelerations, including gravity. Like the semicircular canals, the otoliths can be regarded as biological accelerometers. Once a constant speed is achieved, the otoliths return to their resting position and subsequently no longer signal motion.

Vestibular system's response

Because of its mechanical properties, vestibular self-motion perception is limited and may lead to erroneous percepts. As already mentioned, during a period of constant stimulation, the discharge rate returns toward the resting level and hence the vestibular system cannot sense constant velocity motion. Secondly, a sudden stop after constant rotation may lead to an illusory perception of motion in the opposite direction. Neurophysiological and psychophysical studies have also shown that the vestibular self-motion system is less effective (i.e. reduced gain) in signalling low frequency motion and becomes increasingly sensitive to accelerations at higher frequencies (Benson et al., 1986; Benson et al., 1989; Fernandez & Goldberg, 1976; Goldberg & Fernandez, 1971). Consequently, motion at low frequencies (< 0.1 Hz) tend to be underestimated or remains undetected (Howard, 1986a). Finally, linear accelerometers like the otolith organs cannot distinguish gravity from head linear acceleration, but measure the gravito-inertial force (i.e. the vector resultant of gravitational and inertial force). Consequently, the otoliths are

unable to distinguish tilt from translation under certain conditions such as sustained linear acceleration, which can lead illusory sensations of tilt, the so-called somatogravic illusion (Clark & Graybiel, 1949). Because the stimulus to the otoliths is a change in the gravito-inertial force vector, the otolith signal can be interpreted as a change in direction with respect to gravity, and a linear acceleration.

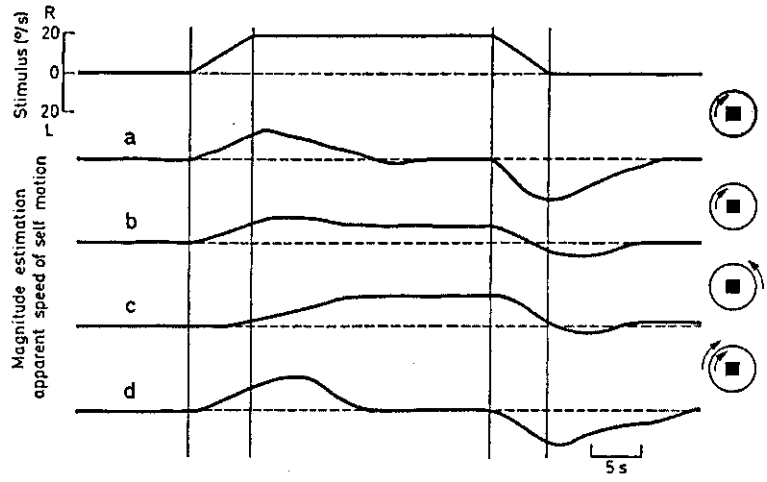


Fig 1.3 Recordings of continuous tracking of perceived self-motion velocity and direction during chair and/or surround motion (trapezoid velocity profile, top trace). (a) During chair rotation in the dark the velocity profile roughly follows mechanical characteristics of cupula-endolymph system resulting in a lack of constant velocity discrimination and consequent misinterpretation of deceleration. (b) With visible surround providing adequate optokinetic information these deficiencies are largely compensated. Net visual effect is demonstrated in (c) where (with considerable latency) apparent self-rotation is elicited in a stationary observer through exclusive surround motion in opposite direction. (d) If visual surround moves with the observer motion perception is again erroneous since, as in (a), it exclusively relies on vestibular inputs (from Dichgans & Brandt, 1978).

Under most conditions, the limitations of the vestibular system can be overcome by the integration of self-motion cues provided by other sensory organs, most importantly the visual system. This was elegantly demonstrated in an optokinetic drum study by Dichgans and Brandt (1978). Observers were exposed to either exclusive body rotation (no visual input), rotation of the visual surround (no vestibular input), or a combination of both. As predicted, based on the mechanic properties of the semicircular canals, during constant rotation in the dark the perception of motion gradually decreased and was absent after about 20 seconds (figure 1.3a). Figure 1.3a also shows the negative after-effect

in the decelerating phase as discussed above. The veridical perception of continuous self-rotation was however maintained in the presence of visual information during rotation in the light as would occur under natural conditions (figure 1.3b). In figure 1.3c, the effect of exclusive surround motion is illustrated (i.e. optokinetic drum stimulation), which gradually induced the perception of self-motion (the visually induced perception of self-motion, or vection, will be discussed in more detail in the following section). Finally, figure 1.3d shows the time course of self-motion perception under conditions in which the visual surround moved with the observer (as would occur whilst travelling in vehicles without outside view), which again resulted in an erroneous percept since it exclusively relies on vestibular inputs similar to the situation described in (a).

1.2.2 Visual information

Gibson (1950) coined the term 'optic array' to describe the projection of light on the retina. Motion of either the observer relative to the environment or of objects relative to the observer results in deformations of part or all of the optic array. Gibson described the continuous deformation of retinal images as a pattern of flow. When moving forward along a straight path, an observer receives an expanding motion pattern of visual images that radiates outward in all directions from the focus of expansion (FOE), the position in the field where the optic flow is zero. The FOE indicates the direction of self-motion or heading (figure 1.4). When head movement through space occurs perpendicular to the direction of looking, as in looking to the side while moving forward, the flow of images moves horizontally across the retina and is referred to as lamellar optic flow (Koenderink, 1986).

This optic flow pattern contains normally reliable information regarding the observer's velocity, travelled distance, heading, and distance from surfaces (Bremmer & Lappe, 1999; Gibson, 1966; Lee, 1980; Nakayama & Loomis, 1974; Warren & Hannon, 1988). The significance of optic flow becomes particularly apparent when it is not matched to the true self-motion. For instance, Lee and Aronson (1974) showed that toddlers that have just learned to walk fall over when the walls of a surrounding room are set in motion. Finally,

as already mentioned, optic flow can induce an illusory feeling of self-motion in stationary observers opposite in direction to that of the visual stimulus.

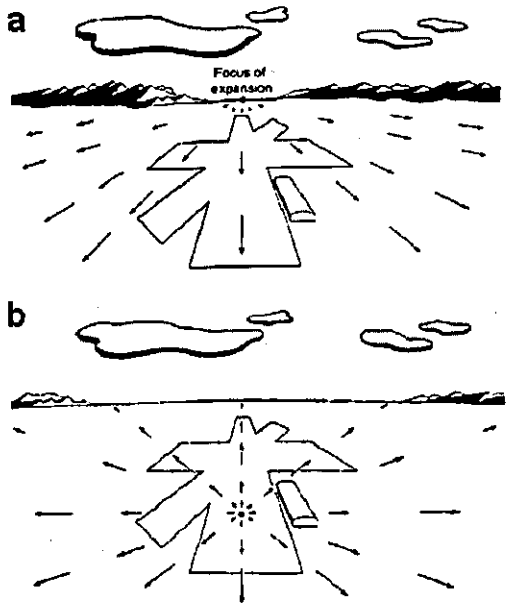


Fig 1.4 Example of a radially expanding optic flow pattern produced by observer translation. The position of the Focus of Expansion (FOE) informs the observer the direction of heading. In (a) flight is level with the ground. In (b) the heading direction is towards the ground (from Gibson, 1966).

Considering its central role within virtual environments and the occurrence of VIMS, the following provides a basic understanding and general findings with regard to vection. Space restrictions prohibit a detailed discussion of the vast experimental work in this area and the interested reader is referred to Dichgans and Brandt (1978), Howard (1982; 1986b), Berthoz (2000), and Hettinger (2002) for excellent discussions on self-motion perception and vection in particular.

Vection

The visually induced perception of self-motion is known as vection (Tschermak, 1931). It was reported long ago since it may occur under natural conditions, such as gazing down on a river standing on a bridge, or viewing a train starting on the adjacent track (Helmholtz, 1896; Mach, 1875). In general, visual movement can be perceived as either object- motion or self-motion. The fact

that moving scenes may be interpreted as the result of self-motion instead of object-motion of the background can be understood based on the assumption of a stable environment (Dichgans & Brandt, 1978). In everyday experience, the visual surround rarely moves uniformly unless the body moves relative to the Earth. Hence, when the environment appears to move, as in a dynamic display, we are more inclined to attribute the relative movement to ourselves instead of the surroundings. Such scenes can thus serve as "frames of reference" with respect to which perceived relative motion is more likely to be attributed to self-motion than object motion (Howard, 1982). Conversely, individual objects are not necessarily Earth-fixed. That is, if we see individual objects or groups move with respect to us, it seems ecologically plausible to conclude that the perceived relative motion is due to the objects moving rather than our own movement.

Vection can be induced by viewing visual representations of motion in any of the linear or rotational axes of the body or a combination thereof (Dichgans & Brandt, 1978; Hettinger, 2002). As any body motion through space, vection kinematics are conventionally described with respect to the fore-and-aft or sagittal x-axis, the left-right or lateral y-axis, and the head-foot (up-down) or spinal z-axis (Hixson et al., 1966). *Linearvection* refers to illusions of translation along one of these three axes, whereas *circularvection* refers to illusions of rotation around one of these axes (roll, pitch, and yaw around the x-, y-, and z-axes, respectively).

Before various display technologies (e.g. HMD, CAVE, large-screen projection systems) and computer generating image technologies became affordable and available, vection was studied using a variety of devices. Circularvection about the upright body's z-axis (also known as yaw vection) has been most commonly investigated by placing a subject inside an optokinetic drum, i.e. a large drum with vertical black and white stripes painted on its inside wall that can be rotated around an observer seated inside on a stationary chair (Brandt et al., 1973; Wong & Frost, 1978; Young et al., 1973). Roll and pitch vection have been induced by devices such as circular disks with a patterned surface that are positioned in front of an observer or hollow spheres with a patterned inner surface that are set in motion around an observer (Dichgans et al., 1972; Held et al., 1975; Howard et al., 1988). Linearvection has been studied using varying

devices, including moving rooms (Lee & Aronson, 1974; Lishman & Lee, 1973), devices that incorporate projection of linear optical flow patterns onto the walls of a stationary room in which an observer is standing or seated (Berthoz et al., 1975; Lestienne et al., 1977), and frontal presentation of motion patterns (Ohmi & Howard, 1988).

Yaw vection is by far the most thoroughly and frequently investigated form of vection (e.g. Brandt et al., 1973; Wong & Frost, 1978; Young et al., 1973). Once the optokinetic drum has been set in motion, individuals initially perceive the drum correctly as rotating and do not perceive self-motion (i.e. there is a veridical perception of object motion). This is followed by a period of apparent subjective acceleration together with the apparent deceleration of the rotating drum, which may last for several seconds. Finally, typically after about 20 to 30 seconds, the drum is perceived as completely stationary in space and the perceived velocity of self-motion does not seem to increase any further, a stage called 'saturated vection' (Brandt et al., 1973). This sensation continues, but may be intermittently interrupted by abrupt changes between the non-veridical sensation (self-motion) and the veridical sensation (drum rotation) (Young et al., 1973) and is referred to as 'bistability' of vection. After drum rotation has stopped, and in the absence of visual input (lights off), a positive aftereffect has been observed whereby the observer continues to feel him/herself rotating in the same direction, followed by a negative aftereffect (Brandt et al., 1974). A similar phenomenology has been observed with respect to linear motion (Andersen & Braunstein, 1985; Berthoz et al., 1975).

The delay in vection onset is a general finding in all forms of vection (Berthoz et al., 1975; Dichgans & Brandt, 1978) and is generally ascribed to the presence of visual-vestibular conflict. According to the 'visual-vestibular conflict' theory (Young, 1970; Young et al., 1973; Zacharias & Young, 1981), when a stationary observer is being exposed to a sudden onset of a moving visual stimulus they should initially perceive themselves as stationary. This is because of the following visual-vestibular conflict: the step change in visual field velocity implies a visual acceleration impulse which is above the threshold of the vestibular system, but is definitely not confirmed by vestibular signals which continue to indicate constant (zero) velocity. With prolonged stimulation, however, vection

can develop and dominate, since any constant linear velocity is consistent with the vestibular signal at rest. This also explains the fact that when a neighbouring train pulls out of a railroad station the sensation of vection is most effective when the acceleration of the visual field is low (Berthoz et al., 1975). As mentioned earlier, the high-pass characteristic of the vestibular system renders it relatively insensitive to low accelerations.

Further support for the role of visual-vestibular conflict comes from findings that concordant inertial cues, i.e. an impulsive rotation of the body in the direction of the illusory self-motion, can speed up the onset of vection (Brandt et al., 1974; Wong & Frost, 1981), whereas actual vestibular stimulation counter to the scene motion destroys the sensation of vection (Young et al., 1973). Also, under conditions in which the vestibular system is rendered less sensitive, vection is more readily induced. Vection onset latencies are significantly shorter in patients with Ménière's disease (Wong & Frost, 1981), individuals with lower vestibular sensitivities (Lepecq et al., 1999), during parabolic (Liu et al., 2004) and space flight (Young et al., 1986), and when adopting a supine position or inclining one's head (Howard, 1986a; Young et al., 1975).

The concept of visual-vestibular conflict also provides an explanation for the paradoxical sensation of continuous rotation of the body whilst feeling tilted at a more or less constant and limited angle of tilt (Dichgans et al., 1972; Held et al., 1975; Howard et al., 1988). According to the otolith-restraint hypothesis (Held et al., 1975), this phenomenon is ascribed to the restraining influences from the otoliths, which signal that the body is not actually being tilted (cf. Howard & Childerson, 1994). It further explains the finding that simulated self-motion about the yaw axis results tends to induce greater vection magnitude ratings than rotation about the pitch and roll axes (Howard et al., 1988). Unlike pitch and roll motion, rotation about the yaw axis would not normally be accompanied by stimulation of the otoliths.

A further general finding is that vection is more readily induced at lower frequencies. Unlike the vestibular system which fails to render low frequency or constant velocity motion (i.e. high pass characteristics) (Fernandez & Goldberg, 1971, 1976), the response of the visual system in this respect is considered to have low pass characteristics (e.g. Andersen & Braunstein, 1985; Howard,

1982). Young (1978) noted that circularvection can be induced with sinusoidal pattern motion frequencies of up to 1 Hz. Beyond this frequency, vection was found to rapidly decrease. A similar frequency dependence has been observed for horizontal and vertical linearvection (Berthoz et al., 1975; 1979). Over the frequency range 0.01 to 1 Hz, vection magnitude was found to decrease with increasing frequency. Based on the different frequency response characteristics of the visual and vestibular system, it has been suggested that the vestibular high-pass signal is centrally transformed into a broad band-pas signal for self-motion perception, by fusing it with a visual signal that has been given complementary low-pass properties (Zacharias & Young, 1981). In this way, the combination of visual and vestibular inputs reduces the shortcomings of either transfer characteristics alone and self-motion perception becomes independent of stimulus frequency in the 'standard' condition of everyday life. It should be noted that it is currently unclear how the brain exactly establishes this visual-vestibular integration process and this forms a matter of debate (see Laurens & Droulez, 2004; Mergner et al., 2000; Reymond et al., 2002).

Factors affecting vection

A number of studies have elucidated several factors relating to the stimulus and the experimental setting that can moderate the onset time, duration, and magnitude of vection. Traditionally, it was believed that a necessary condition for vection to occur was the stimulation of peripheral vision. In a widely cited optokinetic drum study by Brandt et al. (1973) it was reported that circular displays 30° or 60° in diameter presented from 45° to 75° in the periphery were sufficient to evoke vection similar to that evoked during full-field stimulation. A stimulus covering the central 60° region, on the other hand, had a reduced effect whereas one covering a 30° region had no effect at all. These results led to the conclusion that peripheral stimulation plays a dominant role in circularvection. However, this study has been criticised for a number of reasons. First, the peripheral stimulus covered a larger area than the central stimulus (Howard & Heckmann, 1989; Post, 1988). Post (1988) replicated Brandt et al.'s study equating central and peripheral displays in terms of area and found that vection was reported with 30° displays placed in both the peripheral and central

visual field. Secondly, due to the configuration of the experimental apparatus in Brandt et al.'s (1973) study, the perceived distance of the peripheral displays was greater than that of the central displays (Howard & Heckmann, 1989). When there are multiple displays in view, it has been shown that vection is induced by displays that appear to be in the background (Howard & Heckmann, 1989; Ohmi et al., 1987). This can be explained by the fact that, in general, more distant scenery is less likely to be in motion than are objects nearby. Nearby moving objects, on the other hand, will usually be in motion against a background of more distant visual contours which are not in motion or attached to oneself (Howard & Heckmann, 1989).

A further study often cited as demonstrating the importance of peripheral stimulation is that of Johansson (1977). In this study, vertically translating displays of 10°-30° positioned in the central visual field failed to induced linearvection, whereas 10° bands place 45°-80° in the periphery along did so. However, as pointed out by Telford and Frost (1993), screens providing occlusion edges were used to restrict the motion to the periphery, but no equivalent condition was run to restrict motion to the central visual field. As a result, relative depth cues were available in the peripheral display condition only. Several studies have shown that relative motion of seen parts of the own body (e.g. visible parts of the orbital rims) or external stationary objects in the foreground relative to the scene (e.g. fixation point) facilitate vection (Becker et al., 2002; Brandt et al., 1975; de Graaf et al., 1991; Henn et al., 1980; Howard & Howard, 1994; Mergner et al., 2000; Riecke et al., 2004). In contrast, stationary objects beyond the moving display hinder the strength of vection (Howard & Howard, 1994).

Apart from acting as a relative depth cue resulting in the moving scene being interpreted as background, the facilitating effect of stationary objects during optokinetic drum stimulation has been related to the Duncker illusion, i.e. the apparent motion of a stationary spot counter to the direction of pattern motion (Duncker, 1929). Mergner et al. (2000) suggested that initially the Duncker illusion creates a conflict in that the observer cannot gaze at an apparently moving object and, at the same time be stationary and make no eye movements. They argued that this ambiguous perceptual state facilitates the

occurrence of vection, which helps to resolve this conflict: ones vection starts, the body and the object are perceived as moving in perfect synchrony with each other in space.

The most convincing findings that argue against the peripheral dominance theory of vection is that central displays consisting of radial optic flow can reliably induce linearvection along the line of sight (Andersen & Braunstein, 1985; Ohmi & Howard, 1988; Telford & Frost, 1993). Using a radially expanding flow pattern simulating movement through a 3D cloud of dots, Anderson and Braunstein (1985) demonstrated that vection can be induced by stimulating an area in the central visual field as small as 7.5°. Telford and Frost (1993) systematically investigated the effect of optic flow structure and sources of internal and external depth information on linearvection using random-dot displays. Their results showed that, contrary to expectations based on the peripheral dominance theory, vection strength actually decreased when radial displays were placed towards the periphery. Linearvection was also found to be reported sooner and experienced as more compelling with radial displays than with lamellar displays of the same size. This effect persisted even after masking large parts of the central visual field indicating the preference for radial optic flow was not restricted to the central visual field as previously suggested by others (Stoffregen, 1985; Warren & Kurtz, 1992). Since the flow structure in the far periphery of radial displays is similar to the structure of lamellar displays (Koenderink, 1986), Telford and Frost (1993) argued that the increased effectiveness for inducing vection is a function of the internal depth cues in radial displays, rather than their flow structure. In radial displays, each dot or element is in a different simulated location in depth, whereas in lamellar displays, all of the elements are in the same simulated depth plane. Additional internal depth cues including increased dot velocity and size towards the periphery may also have played a role although it was shown that changing velocity only was effective in maximising vection. Further, unlike radial displays, lamellar displays were able to induce linearvection only in the presence of a viewing booth in which subjects sat, confirming earlier findings (see above) that occlusion information facilitates vection. This may explain the inability of earlier studies to induce circular or linear vection with small displays because the

requisite depth cues to specify the moving surface as far were missing (Telford & Frost, 1993). Telford and Frost concluded that in the absence of internal depth cues as in lamellar flow patterns, the necessary depth segregation can be provided by monocular occlusion information. These cues are however not required with displays in which depth cues form an integral part as in radial displays.

A further factor that reliably affects the velocity and intensity of vection is the optical velocity of the stimulus pattern. Howard (Howard, 1986b) reported the general finding that the apparent velocity of circularvection is directly proportional to optical velocity up to values of about 90°/sec, although it should be noted that this relationship is influenced by the spatial frequency (texture density) of the stimulus pattern (de Graaf et al., 1990). Although the general pattern is largely the same, the upper limit varies somewhat between different studies which may be, at least partly, explained by differences in the specific spatial frequencies and experimental procedures employed. Brandt et al. (1973) and Dichgans and Brandt (1973) observed that velocity perception of circularvection is linearly related to stimulus velocity up to about 90 to 120°/sec, beyond which the perceived vection velocity lags behind stimulus velocity. Kennedy et al. (1996b) were able to induce circular vection up to 200°/sec. Young (1978), on the other hand, observed that vection intensity steadily increased with increasing velocity with an upper limit of only 60°/s after which vection was reduced rapidly and the visual pattern perceived as unstable or just moving. Similar findings were observed by Hu et al. (1989). With regard to forward linearvection, Berthoz et al. (1975) observed a similar pattern. The sensation of motion linearly increased with increasing velocity up to the point of saturation. Similar to circularvection, the sensation of motion broke down after exceeding a certain image velocity (2.8 m/sec).

Besides the temporal frequency, the number and density of moving contrasts, i.e. the spatial frequency, has also been shown to influence the effectiveness of a moving visual scene. Brandt et al. (1975) showed that roll vection increased with increasing the number and density of elements and reached an asymptote after 30% of the visual field was subtended by randomly distributed elements. In an optokinetic drum study, Hu et al. (1997) investigated the effect of spatial

frequency by covering the inside of the drum with 6,12, 24, 48, and 96 pairs of black and white stripes. Unlike Brandt et al.'s findings, vection reached a maximum at the intermediate spatial frequency of 24 stripes above which the sensation of vection decreased.

Finally, as already noticed by Mach (1875), the occurrence of circularvection is facilitated by the fixation of a stationary spot in front of the moving pattern. This suppresses the optokinetic reflex (OKR) and causes the pattern to sweep across the retina. In contrast, the perceived angular velocity was thought to be independent of whether OKR is allowed to develop or not (Dichgans & Brandt, 1978). De Graaf et al. (1991), however, reported an increase in circularvection velocity during periods of fixation by a factor of about 1.6. De Graaf et al. related this observation to the Aubert-Fleischl paradox, according to which the perceived speed of a moving object is larger when the eyes are stationary as compared to when they track the object (Dichgans et al., 1969). Similarly, Mergner et al. (2000), using low-frequency sinusoidal motion instead of constant-velocity motion, found larger circularvection when observers fixated at a stationary spot than when they stared at the moving pattern and could develop OKR. It is however not clear whether the enhanced circularvection magnitude observed during fixation in these experiments is due to differences in afferent and efferent velocity perception, as De Graaf et al. suggest, or to the Duncker illusion (Duncker, 1929), i.e. the apparent motion of the spot counter to the direction of pattern rotation. The Duncker illusion creates a conflict: the observer cannot gaze at an apparently moving object and, at the same time, be stationary and make no eye movements. This conflict resolves once vection starts, hence the facilitating effect of fixation on circularvection (Mergner et al., 2000). However, as a second effect, after vection has been established, the continuing relative motion between pattern and fixation spot also might act to enhance the perceived magnitude of self-rotation (Howard & Howard, 1994).

As illustrated by the above studies, research on the perception of visually induced self-motion has traditionally focussed on bottom-up factors (i.e. physical stimulus properties). However, cognitive or top-down factors such as previous knowledge, expectancy, or attention, can also affect the perception of self-motion (Guedry, 1974; Henn et al., 1980). For example, Lepecq et al.

(1995) has shown that vection onset latency was reduced when participants were seated on a movable chair as compared with a chair that could not move indicating that knowledge that physical motion is possible affects the onset of vection (see also Andersen & Braunstein, 1985). Palmisano and Chan (2004) have shown that asking participants to focus on the onset of self-motion biases them to report an earlier vection onset, compared with the situation where they were asked to report the offset of object motion while watching the identical stimulus. Kitazaki and Sato (2003) demonstrated an attentional modulation of vection. In this study observers were exposed to upward and downward moving dots of different colour projected at the same depth plane. Dots moving in the same direction had the same colour, and observers were asked to attend to one of the two colours. Unlike most visual phenomena which require directed attention on behalf of the observer, vection was perceived in the direction opposite to that of the non-attended motion. Riecke et al. (2006) have further demonstrated that abstract visual stimuli (e.g. random dot patterns) are less effective in inducing vection as naturalistic visual stimuli. Photorealistic images were found to be more effective in inducing yaw vection than modified versions of the same stimulus created by slicing the original image horizontally and randomly reassembling it or by scrambling image parts in a mosaic-like manner. According to the authors, naturalistic scenes provide observers with a convincing reference frame for the simulated environment thereby facilitating the attribution of relative motion to self-motion rather than object motion. Following a similar argument, Bonato and Bubka (2006) showed that chromaticity and spatial complexity facilitated vection. Vection was experienced sooner and more compelling when the inside of an optokinetic drum was covered with coloured stripes rather than black and white stripes. Similarly, a black-and-white checkerboard pattern was found to be more conducive to vection than simple black-and-white stripes.

1.2.3 Proprioception

In addition to the visual and vestibular system, self-motion is sensed by proprioceptors. Strictly speaking, proprioception refers to knowledge of the body in general. However, in the present context, proprioceptors refer to

mechanoreceptors of the joints and muscles from which the position of the individual joints and therefore limbs can be reconstructed (Matthews, 1988).

Proprioception can provide powerful information about self-motion. For example, knowing about the movement of the feet during walking and the length of the stride carries enough information to calculate the distance covered. Under normal circumstances, proprioception adds confirmatory evidence of self-motion to the information received from the visual and vestibular system. However, stimulation of proprioceptors may result in motion illusions under some conditions. For example, individuals may experience vection when they link their arms to a drum that rotates about them and thereby generates "arthrokinetic" input from the shoulder joints (Brandt et al., 1977). Similarly, stimulation of tactile receptors in the palm of the hands by a moving rail and stimulation of the feet by a moving platform also may produce vection (Lackner & DiZio, 1984). Finally, Kolev and Rupert (2004) investigated the role of air stream on the perception of self-motion. Using an optokinetic drum with an air blower attached to the sphere wall and directed to the subjects' face, it was shown that the rotating air current, through the sense of touch, not only facilitated the visually evoked perception of self-motion but was also shown to be potent enough to induce vection by itself. The existence of these types of vection indicates a convergence of vestibular and proprioceptive afferents.

1.2.4 Efference copy

Self-motion can also be deduced from the efference copy. During an active movement, a copy of the efferent motor command (efference copy) is produced and sent to the cerebellum (von Holst & Mittelstaedt, 1950). Within the cerebellum, this efference copy is stored and then compared with information from the muscles themselves about the actual movement (Sperry, 1950). In addition, having access to a copy of the efferent command allows the brain to prepare for the consequences of an intended motion before it has occurred. This is a widely accepted explanation for our ability to differentiate between movement of the eyes and movement of the world during eye movements, enabling us to maintain a perception of a stable world.

On the basis of their experiments, von Holst and Mittelstaedt (1950) were able to propose that sensory signals that arise from self-activated motion, which they termed re-afference, could be distinguished from the sensory signals from muscle movement that are caused by external sources, which they termed ex-afference. Specifically, the efference copy of the motor command is combined with the afferent sensory signal to selectively cancel the reafferent component caused by the motor behaviour (the reafference principle). Thus, if the expected movement occurs, it confirms the initial intention was correctly carried out. But if the motor command does not agree with reafferent signals associated with muscle activity, an error signal is effectively created. The cerebellum then initiates corrective reprogramming of motor commands so that the movement can be carried out to its original target (Sperry, 1950).

When the head is free to move, for example, efference copy signals are a reliable source of information about intended head movements. It informs the brain exclusively about purposefully executed movements and is therefore categorised separately from proprioceptive information, which produces the same signals regardless of whether the source of the movement is internal or if it is caused by some externally applied force.

Cells have been found in the parietal cortex of monkeys that change their sensory fields before an intended gaze shift (Duhamel et al., 1992). Also, cells receiving vestibular information seem to be able to distinguish between self-generated and externally applied movements (Gdowski et al., 2000; Roy & Cullen, 2001) implying the existence of an efference copy modifying the sensory information during the movement.

1.2.5 Sound

Although auditory-induced self-motion has been reported almost a century ago (e.g. Dodge, 1923), sound has received relatively little attention in this context. Sound fields have been shown to be able to produce both circularvection (J. R. Lackner, 1977; Riecke et al., 2005) and linearvection (Kapralos et al., 2004; Sakamoto et al., 2004) and have further been shown to enhance the visually induced perception of self-motion (Riecke et al., 2004). Although illusory circular

self-motion can be elicited by sound alone, the illusion breaks down once the contours of the experimental room are visible, illustrating the dominance of visual input (Lackner, 1977).

Interestingly, Sakamoto et al. (2004) reported an asymmetry between the subjective magnitude of forward self-motion and that of backward self-motion. This asymmetry is opposite that observed in visually induced vection in which backward vection has been found to be stronger than forward vection (Berthoz et al., 1975). This suggests that auditory and visual information may play complementary roles in spatial perception.

Similar to the finding that naturalistic visual stimuli more readily induce vection (Riecke et al., 2006), auditory induced vection is facilitated when participants are presented with rotating sounds that normally stem from earth-stationary objects ("acoustic landmarks" such as the sound of a fountain), as compared with artificial sounds (e.g. pink noise) or sounds that normally originate from moving objects (e.g. the sound of footsteps or a driving vehicle) (Riecke et al., 2005).

1.2.6 Summary

From the above, it is clear that the perception of self-motion involves a complex multisensory integration process. Under normal conditions, the different sensory systems provide concordant information. However, the veridical perception of self-motion breaks down in situations in which the sensory environment has been artificially altered such as occurs during optokinetic drum stimulation. This may not only result in illusory percepts as shown above, but may also lead to feelings of motion sickness. In the following, the relationship between the perception of self-motion and motion sickness will be discussed in the context of current theories on motion sickness.

1.3 Motion sickness theories

The first written accounts of motion sickness can be dated back to the Greek (Reason & Brand, 1975). Hippocrates reported the ancient seafarers to suffer from seasickness. Remarkably, Hippocrates' assumption that the sickness was caused by the motion of a ship (Tyler & Bard, 1949) was not taken up again by scientists until the 19th century. Early theories (e.g. Whiting, 1838) suggested that sickness was caused by motion of the stomach contents stimulating the gastric wall and thereby causing gastric contractions ultimately inducing the vomiting response. Other theories hypothesised sea sickness to be caused by the variations of blood supply to the brain (e.g. Leeson, 1878). Irwin was the first, in 1881, to see the connection between the vestibular system and the generation of motion sickness symptoms, which is still the dominant view with respect to the anatomical mechanisms involved in the aetiology of motion sickness. Moreover, Irwin recognised that motion sickness not only occurred aboard ships, but may also be induced by various other motions and hence used the term motion sickness instead of seasickness. Until the 1960s, motion sickness was thought to be caused by both vestibular overstimulation (De Wit, 1953) and insufficient adaptation capacity of the vestibular system (Krijger, 1954). It was again Irwin, however, who first introduced the concept of sensory conflict, a concept which has become the foundation of the most widely accepted theory of motion sickness to date, the sensory conflict theory (Reason & Brand, 1975; Reason, 1978). Other theories have also been proposed including a vestibular-blood pressure hypothesis (Yates et al., 1998), subjective vertical-conflict theory (Bles et al., 1998), postural instability theory (Riccio & Stoffregen, 1991) and an eye movement theory (Ebenholtz et al., 1994). These theories will be briefly discussed below.

1.3.1 Sensory conflict theory

The sensory conflict theory, or neural mismatch theory, states that *"all situations which provoke motion sickness are characterised by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular systems and the nonvestibular proprioceptors are at variance not only*

with one another, but also with what is expected on the basis of past experience" (Reason & Brand, 1975).

Whereas in earlier versions of the theory (e.g. Claremont, 1931) conflict signals were assumed to result from a direct comparison of signals provided by different sensory modalities (e.g. the signals from the visual and vestibular system do not agree), Reason (1978) stressed that the conflict is more likely to involve a comparison between actual and anticipated signals. There are a number of reasons for this. First, continued exposure to provocative motion will result in habituation despite the continuous presence of conflicting actual sensory signals. Secondly, visual and vestibular responses on congruent motion stimuli always differ from one another. As discussed above, these signals are primarily complementary containing mainly high frequency (vestibular) and low frequency (visual) motion information. Subsequent integration in the CNS of these different information signals provides a signal that corresponds to the actual stimulus and a correct spatial orientation can be maintained in this manner without motion sickness. For these reasons, Reason (1978) proposed a more elaborate version of the 'sensory conflict' theory, the 'neural mismatch' hypothesis, stating that the conflict results from a comparison between actual and anticipated signals.

Based on earlier interrelated work by von Holst and Mittelstaedt (1950) and Held (1970), Reason proposed two structural components: a CNS neural memory unit ('neural store'), and a comparator unit. The neural store is thought to retain the essential characteristics of previously encountered sensory environments by storing previously experienced efferent/reafferent 'trace pairs'. The second component, the comparator unit, subtracts reafferent information selected from the neural store from information currently being signalled by the spatial senses.

Based on the model by Reason and Brand (1975) and Reason (1978), others succeeded in the attempt to bring the theory into some congruence with models of spatial orientation perception, such as those formulated by Young (1970), Zacharias and Young (1981), Oman (1982), Borah et al. (1988), Merefeld et al. (1993), and Benson (1988). The basic mechanisms are similar in all these models and will be illustrated by the model as proposed by Benson (1988).

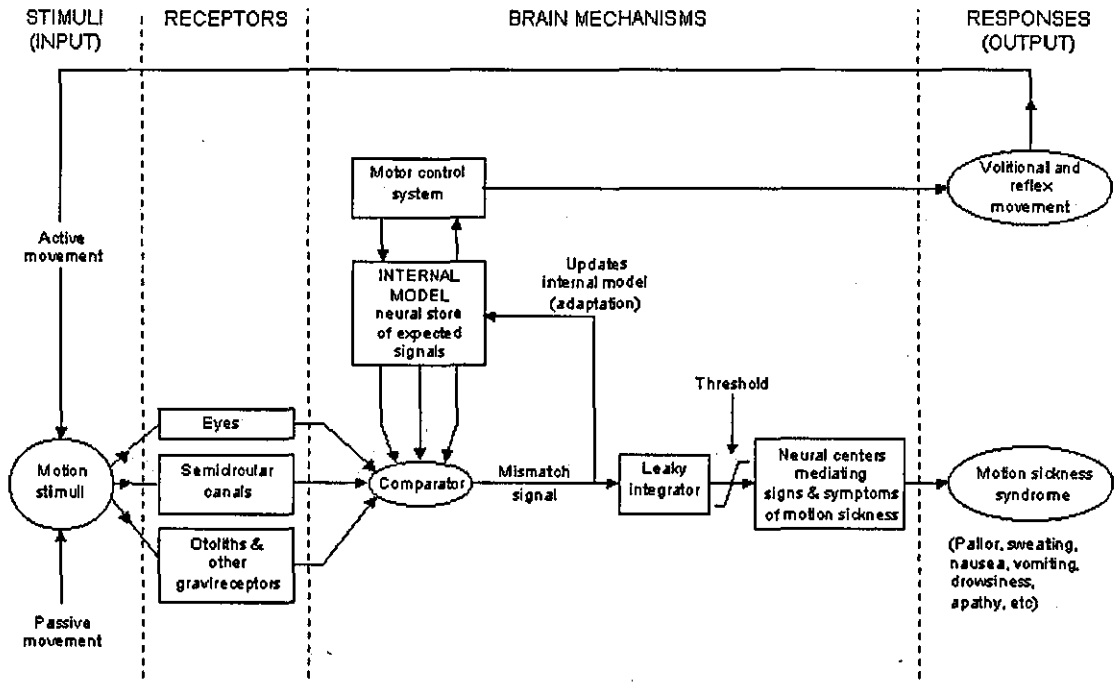


Fig. 1.5 Diagrammatic representation of a model of motion control, motion detection and motion sickness compatible with the 'neural mismatch' hypothesis (adapted from Benson, 1988).

Figure 1.5 shows a diagrammatic presentation of the neural mismatch model (Benson, 1988). Motion stimuli (active and passive) are detected by the visual system, vestibular apparatus, and the nonvestibular proprioceptors. The resultant signals are then compared with the 'expected' signals provided by the internal model (the 'neural store'). The internal model is a model of the afferent and efferent activity associated with body movement and postural control; a model that is built up from continued experience of motor activity in everyday life. In normal locomotor activity, disturbances of body movement, such as when one trips or is pushed unexpectedly, are typically brief and the mismatch between actual and expected information from the body's motion detectors is employed to initiate corrective motor responses. A sustained mismatch signal, however, indicates that the internal model is in error and is no longer appropriate and causes a rearrangement of the internal model. The updating of the internal model clearly has benefits since it allows the individual to function more effectively in the novel motion environment, i.e., the signals are no longer perceived by the brain as being in conflict and the individual may be considered

to have habituated[1] to the atypical motion environment. A second effect of a sustained neural mismatch is the activation of the leaky integrator. This leaky integrator accumulates signals of abnormal inputs, which are 'allowed' to leak away over time. The presence of a leaky integrator has been incorporated to account for the relatively slow development of symptoms on exposure to provocative motion. To account for the fact that not all provocative motion stimuli generate symptoms of motion sickness, particularly if the stimulus is not intense, a threshold function has been integrated in the model. The threshold function prevents the evocation of the sequence of neural and hormonal responses that constitute the motion sickness syndrome, as long as the accumulation of the signals of abnormal inputs does not reach the threshold. It has been suggested that the rate of leaking and threshold level explain the vast differences in susceptibility in motion sickness between individuals (Benson, 1988).

As already stated, in the presence of sensory conflict, there is an attempt to rearrange the internal model. When an individual is repeatedly exposed or exposed over a prolonged period of time to a provocative stimulus, there is a reduction and eventual disappearance of symptoms. In most cases, excluding approximately 5% of the population, these 'habituation' sessions can be utilised to 'desensitise' individuals against motion sickness (Reason & Brand, 1975). After an individual has habituated to a stimulus, an interesting phenomenon may occur when the individual must re-habituate to the normal sensory input if it is removed. This phenomenon, seen in sailors returning to land, is termed *mal de débarquement*. On return to the previous environment, the revised neural store is no longer appropriate and the resulting mismatch may once again generate motion sickness. This re-habituation however proceeds more quickly than the initial habituation to the atypical environment since the correlations

[1]In the motion sickness literature, the terms 'adaptation' and 'habituation' are often interchangeably used. As pointed out by Griffin (1990), the term adaptation is generally reserved for situations where repeated exposure to a stimulus renders the relative sensory organ less sensitive (e.g. dark adaptation of the eye). This has however not been shown to occur with motions causing motion sickness and does not explain the manner in which motion sickness susceptibility varies with exposure to provocative motions. Here, the term 'habituation' is preferred as this refers to situations where a change in response to stimulation involves activity of the CNS.

established by long experience are assumed to be more easily retrieved than new ones can be acquired. Following this same rationale, habituation on return to the atypical environment is likely to be a more rapid process than on first exposure. The updating of the neural store will be more efficient by retaining the stimulus patterns acquired during previous exposures to the atypical environment. Long-term habituation, however, is generally assumed to occur only when exposures are less than one week apart (Bagshaw & Stott, 1985; cf. Hodder & Howarth, 2003).

Whereas updating of the internal model is clearly advantageous as this allows for habituation to take place, the functional significance of the onset of motion sickness symptoms is less apparent, and is still a matter of debate. According to Treisman's (1977) evolutionary hypothesis[2], motion sickness is a tool for survival and the CNS misinterprets the sensory conflict caused by motion as evidence that the body has ingested a toxin. Treisman proposed that since the systems involved in controlling movement, including eye movements, and in determining the location of the body in space, are complex, in action continuously, and are susceptible to even a minor degree of disruption, they constitute an ideal warning system for detecting early central effects of neurotoxins. However, considering the relatively long time required for a toxin to affect central vestibular mechanisms, vomiting is unlikely to be useful in removing toxins from the gastrointestinal tract (Yates et al., 1998). Benson (1988) suggested that the emetic response may just be a design defect, which, in an evolutionary time scale, has only recently become apparent with the use of mechanical aids to transportation.

Motion sickness occurs in a wide variety of circumstances. As already mentioned, true motion is not a necessary condition for the symptoms of motion sickness to occur as similar symptoms may be purely visually induced. Considering the diverse range of causative methods of motion sickness,

[2] Treisman's evolutionary theory is often presented as a separate theory regarding the aetiology of motion sickness (e.g. Flanagan et al. 2004). However, this theory tries to provide an answer as to *why* humans and animals respond to motion sickness the way they do, but says nothing about why we get sick in the first place. For this reason, this theory is not regarded as a theory of motion sickness as such and will not be separately discussed in this paper.

Reason and Brand (1975) suggested classifying different types of sensory conflict into two broad categories: (1) inter-modality: between the visual system and the vestibular receptors, and (2) intra-modality: between the semicircular canals and the otoliths within the vestibular system. These two categories can be further sub-divided into Type 1, Type 2a, and Type 2b conflicts (see Table 1.1).

TABLE 1.1 TYPES AND CATEGORIES OF SENSORY CONFLICT (From Griffin, 1990).

	Category of conflict	
Type of conflict	Visual (A) – Vestibular (B)	Canal (A) – Otolith (B)
Type I (A and B together)	Visual and vestibular system simultaneously signal different (i.e. contradictory or uncorrelated) information.	Canals and otoliths simultaneously signal different (i.e. contradictory or uncorrelated) information.
Type 2a (A in the absence of B)	Visual system signals in the absence of an expected vestibular signal.	Canals signal in the absence of an expected otoliths signal.
Type 2b (B in the absence of A)	Vestibular system signals in the absence of an expected visual signal.	Otoliths signal in the absence of an expected canal signal.

- *Type 1*: A and B simultaneously give contradictory or uncorrelated information. This conflict could be experienced when individuals watching the movements of the waves that do not conform to the motions made by the ship that they are on board. An example of an intra-modality conflict is cross-coupled Coriolis stimulation. Cross-coupled Coriolis stimulation of the semicircular canals occurs when an individual, who is being rotated about a particular axis, moves his head other than in the plane of the imposed rotation. One configuration of canals is taken out of the plane of rotation and is stimulated by the apparent reduction in rotational speed, while another set of orthogonal canals is brought into the plane of rotation which receives a stimulus equivalent to an increase in the rate of turn. The result of this cross-coupled stimulation is to produce an erroneous signal of turn about an axis that accords neither with that of the imposed rotation nor with the axis in which the voluntary head movement is made. Furthermore, the signal from the stimulated canals persists after the movement has been completed, for the deflected cupulae commonly take 10 seconds or more to return to their neutral positions. During this time, the otoliths correctly

sense the true attitude of the head with respect to gravity. Hence, there is a mismatch between the otolith signal and that from the canals. This cross-coupled stimulation has the potential of inducing sickness to all individuals with an intact vestibular system, provided the speed of rotation is high enough, the head movements are repetitive and they are of sufficient amplitude (Miller & Graybiel, 1970).

A type 1 conflict can also occur in earth-fixed HMD-based VR systems as a consequence of update lags associated with the computer recalculation of the virtual scene following a head movement (Draper et al., 2001; Howarth & Finch, 1999; Regan & Price, 1993; So, 1994). In all but the most expensive VR systems, users perceive a delay between the time a physical motion is made (e.g., turning the head to the right) and the time the computer responds with a corresponding change in the display. Because of this update lag, the information received from the vestibular system following a head movement is incongruent with the visual information that the user is receiving from the (moving) image on the screen. In addition, once the head movement is completed the vestibular system records that the head is still, whereas the visual system is recording movement since the screen image is still moving. A similar conflict may be encountered when HMDs are configured as 'personal viewing systems', where head-tracking may be disabled and the HMD becomes a personal screen (Howarth & Costello, 1997). Although visual lag is absent in this situation, sensory conflict may still occur as the motion depicted in the display may be unrelated to actual head or body movements. In addition, the lack of movement of the image may conflict with the expectation of movement as the head is moved.

- *Type 2a*: A signals in the absence of an expected B signal. This type of conflict represents the classic example that is thought to underlie the generation of VIMS. This occurs under conditions in which stationary observers (no vestibular input) are exposed to moving visual scenes as typically occurs during optokinetic drum stimulation or 'riding' a fixed-base simulator. A further example in which this type of conflict is involved is space sickness. The activation of otolith organs that accompanies simple head tilt on Earth does not occur in the absence of gravity, although semicircular canals are still stimulated. However,

linear acceleration in a microgravity environment stimulates otolith receptors. Thus, during some, but not all, movements performed during spaceflight, the combined inputs from otolith organs and semicircular canals that are expected based on experience on Earth do not occur (Oman et al., 1990).

- *Type 2b*: B signals in the absence of an expected A signal. This conflict could be encountered in all modes of passive transport where the passenger lacks a clear view of the visual scene outside the vehicle. This may happen on ships whilst being below deck since the movements of the ship, and hence the information received by the vestibular system, does not correspond to the static visual surround. An intra-modality conflict is evoked by rotating individuals at constant angular velocity about an earth-horizontal axis ('barbeque-spit' rotation). On initiation of the rotation, angular velocity signals from the semicircular canals are in agreement with the changing orientation of the head with respect to gravity indicated by the otoliths. After 10-20 seconds of constant angular velocity rotation, however, i.e., 10-20 seconds after the initial angular acceleration has decayed, the canal information has returned to its rest state and does not indicate any rotation. As a result, the otoliths are stimulated by the continued reorientation relative to the gravity vector and signal rotation, whereas the canals fail to signal rotation.

Although the sensory conflict theory or neural mismatch hypothesis is currently the most widely accepted theory of motion sickness, it is not without its criticism. Most importantly, it has been criticized for being qualitative, unable to indicate how sensory conflict can be measured (e.g. Denise et al., 1996; Griffin, 1990; Kolasinski, 1995; McCauley, 1984; Riccio & Stoffregen, 1991). The sensory conflict theory can be used to anticipate whether some combination of stimuli is likely to induce motion sickness. It can however not be used to predict the extent of any symptoms, or how they depend on the magnitude, type or duration of motion.

1.3.2 Subjective Vertical-conflict model

Reason and Brand's (1975) categorisation of different sensory conflicts has been widely applied in motion sickness research (e.g. Benson, 1988; Griffin,

1990; Guedry, 1991; Reason & Brand, 1975). Bles et al. (1998), on the other hand, suggested that only one type of conflict is necessary and sufficient to explain all different kinds of motion sickness. Although the authors agree that most of the aforementioned conflicts may lead to disorientations and motion illusions, they suggest that motion sickness is primarily provoked in those situations where the determination of the subjective vertical (i.e., the internal representation of gravity) is challenged. This theory can be regarded as a simplification of the sensory conflict theory, and has been termed the 'Subjective Vertical-conflict model'. It asserts that '*all situations which provoke motion sickness are characterised by a condition in which the sensed vertical as determined on the basis of integrated information from the eyes, the vestibular system and the nonvestibular proprioceptors is at variance with the subjective vertical as predicted on the basis of previous experience*' (Bles, et al. 1998).

Bles et al. referred to two examples that led to the development of the subjective vertical-conflict model. Previous studies by the authors showed that after long-duration centrifugation, only head movements that change the orientation of the head relative to the gravity vector provoked motion sickness. In an upright sitting subject, roll and pitch movements of the head were found to provoke motion sickness, whereas yaw movements elicited motion illusions but no motion sickness. In a similar vein, with the subject in supine position, yaw and pitch head movements were found to be provocative, whereas roll motion was not. Bles et al. argued that whereas sensory mismatches may induce motion illusions, motion sickness is only provoked when the determination of the subjective vertical is at stake.

As a further example, Bles et al. referred to the finding by several European research groups that motion sickness rarely occurs during optokinetic drum stimulation and that the motion sickness incidence as a result of optokinetic drum stimulation has been estimated to be lower than 1% despite the absence of corresponding vestibular information. The authors pointed out that these findings are not in agreement with the sensory conflict theory arguing that the optokinetic stimuli create clear differences between the sensed and expected sensory information. According to the authors, the low incidence is however in accordance with their subjective vertical-conflict model as the stimulus (rotation

about the vertical z-axis) is neutral with respect to gravity. It should be noted though, that the virtual absence of motion sickness is not necessarily at variance with the sensory conflict theory. Since the vestibular system responds to accelerations only, constant vection does not create a visual-vestibular sensory mismatch per se as this is the natural stimulus to constant velocity rotation (see also Cheung & Vaitkus, 1998).

The issue is further complicated by the controversy about the nauseogenicity of this type of stimulation. In contrast with the low sickness incidence referred to by Bles et al. (1998), Stern and co-workers (Stern et al., 1989, 1990) have found that optokinetic drum stimulation leads to motion sickness in approximately 60% of individuals. Bles and colleagues ascribed these discrepancies to the use of non-rigid optokinetic drums (J.E. Bos, personal communication, 2004). Unlike the rigid optokinetic drums employed by the above mentioned European research groups, the non-rigid optokinetic drums as used by Stern and colleagues can subsequently lead to incorrect alignments of the drum. This, in turn, may introduce a wobble or sway leading to discrepancies between the sensed and subjective vertical.

Alternatively, the discrepancies may also be ascribed to the fact that vection is not always a steady perceptual experience. As previously discussed, individuals may not only experience a 'drop-out' during which the perception of self-motion switches to object-motion, but also fluctuations in vection strength. Such perceptual changes are not correlated with what would be the appropriate vestibular stimulation, which continues to signal zero (or constant) motion (see also Bubka & Bonato, 2003). Consequently, sensory conflict can be expected to occur to some degree even during constant velocity optokinetic drum stimulation. Whereas this may explain the observed discrepancies in the potency of optokinetic drum stimulation to some extend, it is difficult to see how this can account for the rather large differences in sickness incidence. Although thus far, no studies have directly compared rigid and non-rigid optokinetic drums, the finding that optokinetic drum tilt does indeed significantly increases the level of motion sickness (Bubka & Bonato, 2003) does lend some support for the contention that the higher motion sickness incidence may be, at least partly, caused by misalignment.

Finally, the finding that misalignment of the drum with the vertical brought about by tilting the drum reliably increases the level of motion sickness (Bubka & Bonato, 2003) illustrates the difficulty in falsifying either the subjective vertical-conflict model or sensory conflict theory. The increased nauseogenicity can be ascribed to (i) additional sensory conflict due to the introduction of a wobbling (sway) component that would normally be accompanied by otolith stimulation (Andre et al., 1996; Bubka & Bonato, 2003), or (ii) the fact that the visual stimuli are no longer neutral with respect to gravity thereby affecting the calculation of the subjective vertical (Bles et al., 1998).

1.3.3 Postural instability theory

According to the postural instability theory (Riccio & Stoffregen, 1991), motion sickness results from prolonged instability in the control of posture. The theory states that prolonged postural instability is the cause of motion sickness, and that reductions in the demands on postural control will reduce the incidence and severity of motion sickness. However, to date, no convincing support for the postural instability theory has been provided. Smart et al. (2002) exposed participants to an optical simulation of body sway and reported that in those who reported symptoms of motion sickness, postural instability occurred prior to the onset of these symptoms. However, only three out of thirteen participants became sick, and consequently, no firm conclusions can be drawn from this research. Warwick-Evans et al. (1998) compared the occurrence of VIMS in a group of restrained and unrestrained participants. Their results showed no significant difference between the two groups in terms of the severity of symptoms reported, or in the time taken for the development of symptoms. Furthermore, the results showed a trend in the direction opposite to that predicted by the postural instability theory. In a recent study by Akiduki et al. (2003) in which the development of VIMS and postural instability was examined, and found that, contrary to the predictions made by the postural instability theory, postural instability occurred after the onset of symptoms. Harm (2002) further pointed out that the theory is unable to explain why labyrinth defective individuals do not get motion sickness, and does not provide a clear explanation of why postural instability should actually cause motion sickness.

1.3.4 Eye movement hypothesis

Ebenholtz et al. (1994) proposed that eye movements may play a causal role in the development of motion sickness, a suggestion based partly on the observation that anaesthesia applied to the extraocular muscles (retrobulbar anaesthesia) produces a significant reduction in the incidence of emesis and nausea after strabismus surgery (Houchin et al., 1992). Their hypothesis is based on the premise of a specific neural route between the vestibular system and vagal nuclei mediated by eye movements. That is, afferent signals from vestibular-mediated eye movements (e.g. traction of the extra-ocular muscles mediated by the vestibular nuclei during optokinetic nystagmus) affect the vagal nuclei, resulting in motion sickness. Hence more complex eye movements will produce more afference and, therefore, more motion sickness symptoms.

In an attempt to evaluate the eye movement hypothesis, a number of optokinetic drum studies have been conducted in which optokinetic nystagmus, vection, and motion sickness were investigated under different viewing conditions (Flanagan et al., 2002; Hu et al., 1997; Hu & Stern, 1998; Stern et al., 1990). The general finding in these studies was that the frequency of horizontal nystagmus correlated positively with the severity of motion sickness. Although these studies appear to support the eye movement hypothesis, nystagmus also showed a positive relationship with vection strength. As a consequence of the inability to dissociate vection from nystagmus, it is not possible to decide on the basis of these studies whether the reduction in motion sickness symptoms was due to a reduction of nystagmus, vection, or both.

It was further pointed out by Hu et al. (1997) that a fast frequency of eye movements in sea sickness, carsickness, and space sickness, is not apparent. Results from a study by Quarck et al. (2000) also question the role of eye movements in motion sickness under conditions of vestibular stimulation. Quarck et al. evaluated the eye movement hypothesis using the OVAR (off-vertical axis rotation) test. This test was employed as it evokes well-defined compensatory eye movements and is highly effective in provoking motion sickness. Results showed no difference in horizontal eye movements between subjects reporting motion sickness symptoms and those reporting no motion sickness symptoms. The authors concluded that, at least with regard to

vestibular stimulation, eye movement characteristics are a negligible factor in the generation of motion sickness.

Thus far, there have been no studies that provided convincing support for the eye movement hypothesis. As suggested by Ebenholtz et al. (1994), perhaps the only way to directly evaluate the eye movement hypothesis may be by exposure to a sickness inducing stimulus after blocking all afference from the extraocular muscles by means of anaesthesia. Not surprisingly, this procedure has hitherto not been adopted.

1.3.5 Summary

Despite its limited predictive value, the sensory conflict theory appears to be valid under numerous conditions and currently provides the most comprehensive framework to guide motion sickness research. For that reason, the work presented here will mainly focus on motion sickness induced by conflicting inputs.

1.4 Visually Induced Motion Sickness

Visually induced motion sickness (VIMS) is here defined as the symptoms experienced by physically stationary individuals in response to viewing visual scenes. From this it follows that VIMS may occur in a wide variety of environments including simulators, virtual environments, but also wide screen cinema or TV. It is however not synonymous to Simulator Sickness (Kennedy et al., 1990b) or any of the terms used to describe the negative side effects following exposure to virtual environments, i.e. Cybersickness (McCauley & Sharkey, 1992), Virtual Simulation Sickness (Howarth & Costello, 1996), or Virtual Reality-Induced Symptoms and Effects (VRISE) (Cobb et al., 1999). This is because these terms, apart from VIMS, refer also to side effects that are not directly a consequence of visual stimulation as such, e.g. effects arising from incorrect calibration of inter-pupillary distance, design viewpoint, stereoscopy, or motion platform.

With regard to the occurrence of symptoms in simulators and virtual environments, a large number of factors have been identified. An excellent overview of these factors has been provided by Kolasinski (1995) who grouped the different factors into three categories: system, individual, and task characteristics (see table 1.2). Rather than addressing all the different factors individually (the interested reader is referred to Kolasinski, 1995), the discussion will focus on factors that have consistently been shown to be related to VIMS.

TABLE 1.2 POTENTIAL FACTORS ASSOCIATED WITH MOTION SICKNESS IN SIMULATORS AND VIRTUAL ENVIRONMENTS (Kolasinski, 1995)

System	Individual	Task
Binocular viewing	Age	Altitude above terrain
Calibration	Concentration level	Degree of control
Contrast	Ethnicity	Duration
Colour	Experience with real-world task	Global visual flow
Field of view	Adaptation	Head movements
Flicker	Flicker fusion frequency threshold	Luminance level
Inter-pupillary distance	Gender	Unusual manoeuvres
Motion platform	Illness and personal characteristics	Method of movement
Phosphor lag	Mental rotation ability	Rate of linear and angular acceleration
Position-tracking error	Perceptual style	Self-movement speed
Refresh rate	Postural stability	Sitting vs. Standing
Scene content		Vection
Time lag (transport delay)		Type of application
Update rate (frame rate)		
Viewing region		

System characteristics. Field-of-view (FOV) and time lag have been shown to be important factors in the occurrence of VIMS. A larger FOV not only induces a stronger feeling of self-motion (Allison et al., 1999; Dichgans & Brandt, 1978), but also leads to higher levels of VIMS (DiZio & Lackner, 1997; Harvey & Howarth, 2007; Ijsselsteijn et al., 2001; Kennedy et al., 1989; Lin et al., 2002). Secondly, increases in delays between information input to, and visual output from, the simulator or VR system (i.e. time lag or update delay) are known to exacerbate VIMS significantly (DiZio & Lackner, 1997; Draper et al., 2001; Howarth & Finch, 1999; Regan, 1995; So, 1994). As already discussed in the context of the sensory conflict theory, time lags may cause temporal discordances between visual and vestibular motion cues (Draper et al., 2001; Howarth & Finch, 1999; Regan & Price, 1993; So, 1994).

Whereas the identification of system characteristics is undoubtedly of value in the context of spearheading technological development, it should be noted that these very much reflect the current state of technology. Future improvements in computing power and display technology can be expected to resolve most issues. However, FOV forms an important technology-independent exception that will remain an issue even in the most sophisticated systems and creates a trade-off between the level of presence and VIMS as both increase with increasing FOV (e.g. Ijsselsteijn et al., 2001; Lin et al., 2002).

Individual characteristics. Individual characteristics that have frequently been associated with the occurrence of VIMS as well as true motion sickness include gender. Although the underlying mechanisms remain elusive, women tend to be more susceptible than men (Clemes, 2004; Golding et al., 2005; Grunfeld & Gresty, 1998; Jokerst et al., 1999; Kennedy et al., 1995; Reason & Brand, 1975; Turner et al., 2000). Ethnicity has also been reported to affect susceptibility to motion sickness with Asian individuals being more susceptible than Caucasian or Afro-American individuals (Klosterhalfen et al., 2005; Stern et al., 1993; Stern et al., 1996). Whether this reflects cross-cultural differences in item responses or biological predispositions is currently unclear (Klosterhalfen et al., 2005). It has further repeatedly been shown that larger experience with the real world task renders individuals more susceptible when performing the same task in a simulated environment (e.g. experienced pilots vs. novices) (Kennedy et al., 1987; Kennedy et al., 1988). This can be understood in the context of the sensory conflict theory in that real-world experience with the sensory aspects of the particular task might lead to greater sensitivity to discrepancies between the actual and simulated task (Kennedy et al., 1988).

In the discussion on the sensory conflict theory, it was briefly mentioned that repeated exposure to a provocative environment renders most individuals symptom-free. It has generally been assumed that long-term habituation only occurs when exposures are less than one week apart (Bagshaw & Stott, 1985). Stern et al. (1989) reported that participants exposed to vection induced by a rotating drum did not show 'adaptation' with intersession intervals of 4 – 24 days, but did do so when the interval was 2 days. Until recently, however, there have been no studies that have investigated this issue regarding VIMS. Hodder

and Howarth (2003) repeatedly exposed participants to a nauseogenic visual stimulus with different time intervals between sessions ranging from one to seven days. Unlike previous findings, the habituation which occurred was of a similar nature in all of the participant groups regardless of exposure interval and it was concluded that the number of exposures rather than the time interval between them was a more important factor. The degree of habituation was however not uniform across participants, indicating inter-individual differences in rate of habituation.

Although discussed in a different context, Kolasinski (1995) did not include the individual's past history of motion sickness amongst the individual factors. However, previous studies have shown significant correlations between an individual's past history of motion sickness induced by various means of transport, and motion sickness induced by optokinetic drums, simulators and VR systems, suggestive of a common underlying mechanism (Hu et al., 1996; Kennedy et al., 2001a).

Identification of individual characteristics that are related to the occurrence of side effects has some distinct advantages. In the context of managing motion sickness, for example, the ability to predict the likelihood and the extent to which an individual will develop adverse side effects can be subsequently used to develop screening tools. The ability to identify susceptible individuals is of relevance for a number of reasons: i) susceptible individuals may be exposed to special habituation programs ahead of time, ii) it may be necessary to design special VR interfaces to reduce the prevalence of adverse side effects, and iii) exclusion of highly susceptible individuals reduces the risk of compromising experimental studies due to participant drop-out (Kennedy et al., 2001a).

Task characteristics. Task characteristics can be subdivided into characteristics that either directly or indirectly affect VIMS. Direct effects are related to those task characteristics that have no direct bearing on the visual scene motion and include degree of control, duration, luminance level, method of movement, body position (sitting vs. standing), and head movements. Some of the main findings will be discussed below.

It is commonly reported that drivers of cars and pilots of aircraft are usually not susceptible to motion sickness despite the fact that they experience the same motion and visual scenes as their passengers (Geeze & Pierson, 1986; Reason & Brand, 1975; Rolnick & Lubow, 1991). In a more recent study, this was also shown to occur in VEs whereby individuals who were moved passively through a simulated building reported more sickness than those who were able to affect their movements themselves using a joystick (Stanney & Hash, 1998). This moderating effect of control on the generation of motion sickness symptoms has typically been attributed to the presence of muscular activity resulting in a concomitant efference copy. This efference copy is subsequently used to activate an internal model and is thought to facilitate the habituation process (Oman, 1982, 1991; Reason, 1978). However, others failed to replicate Stanney and Hash's findings and suggested that the habituation process may not only be facilitated when individuals are motorically able to anticipate incoming sensory cues as suggested by Oman (1991), but also visually (Diels, 2004).

A further finding that has been observed with regard to both true motion sickness and VIMS, is that on average the degree of motion sickness steadily increases during exposure to a provocative environment (Kennedy et al., 2000; Reason & Brand, 1975). Whilst being immersed in a VE, the likelihood of developing symptoms is further increased when standing as opposed to sitting (Regan & Price, 1993; Stoffregen & Merhi, 2005). This may not be surprising considering that the lack of support whilst standing will lead to appreciably more body sway (i.e. vestibular signalling) thereby increasing the likelihood of visual-vestibular conflict to occur.

Finally, head movements are known to be associated with motion sickness through the mechanisms of Coriolis and pseudo-Coriolis stimulation. Coriolis stimulation occurs when the head is tilted out of the axis of rotation during actual body rotation (Dichgans & Brandt, 1973). Pseudo-Coriolis stimulation occurs when the head is tilted as perceived self-rotation is induced from visual stimuli (Dichgans & Brandt, 1973). Although head movements have been found to significantly increase the level of sickness during circularvection using optokinetic drums (Dichgans & Brandt, 1973; Tiande & Jingshen, 1991), no effect was observed in a VE study (Regan & Price, 1993). It should be noted,

however, that in this study head movements occurred in both conditions, albeit to a different degree, and future, more systematic, work is warranted.

Apart from the above factors which can be thought to affect VIMS directly, most task characteristics influence VIMS in an indirect manner in that operator control behaviour affects the visual stimulus for self-motion. Kolasinski (1995) identified altitude above terrain, global visual flow, unusual manoeuvres, rate of linear and angular acceleration, self-movement speed, vection, and type of application as further task characteristics. Of course, these factors are not independent. More specifically, vection depends on the global visual flow rate which in turn is a function of altitude above terrain, rate of linear and angular acceleration, self-movement speed, manoeuvres, and type of application (i.e. 'far' vs. 'near').

Remarkably, out of 39 studies on which Kolasinski's review was based, only 1 study (Sharkey & McCauley, 1991) directly addressed the question of how visual stimulus characteristics relate to sickness. These authors showed that the level of sickness increased with increasing global visual flow rate, i.e. the rate or speed at which objects flow through the visual scene. Based on these findings, a number of recommendations were made. Since the global visual flow rate is inversely related to altitude (i.e. eye height), lower altitudes result in higher global visual flow rates. Consequently, it was recommended that self-motion in VEs should be at high altitudes above the terrain in order to limit the occurrence of adverse symptoms. The authors further recommended that i) tasks requiring high rates of linear or rotational acceleration should be avoided or kept brief until full habituation to the virtual environment was achieved, ii) self-movement in a VE should be at low speeds, and iii) abruptly freezing the simulation and "flying" backwards should be avoided. Frank & Casali (1986) further recommended that i) situational reset (i.e. rapid forward or backward resetting in time of the scene) should be avoided.

Sharkey and McCauley's study (1991) has provided pragmatic approaches and rules of thumb to minimise the level of sickness occurring in simulators and VR systems. A number of studies have been conducted employing a more systematic and theoretical approach to determine the relationship between visual stimulus characteristics and VIMS. These will be discussed in the following section.

1.5 Previous studies into the effect of visual stimulus characteristics

Table 1.3 shows a chronological overview of studies into the effect of visual stimulus characteristics on VIMS. It can be seen that the vast majority of studies employed optokinetic drums inducing circularvection about the Earth-vertical z-axis. In the following discussion, the different studies will be categorised according to the parameters investigated.

TABLE 1.3 Overview of studies investigating visually induced motion sickness as a function of VISUAL STIMULUS characteristics

References	Platform	Parameter	Motion axis
(Hu et al., 1989)	Optokinetic drum	Optical velocity	Yaw
(Cheung et al., 1991)	Optokinetic sphere	Rotation axis	Yaw, pitch, roll
(Sharkey & McCauley, 1991)	Flight simulator	Optical velocity	Linear x-axis
(Andre et al., 1996)	Optokinetic drum	Rotation axis	Yaw
(Hu et al., 1997)	Optokinetic drum	Spatial frequency	Yaw
(Lo & So, 2001)	HMD	Rotation axis	Yaw, pitch, roll
(So et al., 2001)	HMD	Optical velocity	Linear x-axis + roll
(Kennedy et al., 2001b)	Optokinetic drum	Pictorial realism	Yaw
(Webb & Griffin, 2003)	HMD	Spatial frequency	Linear y-axis
(Bubka & Bonato, 2003)	Optokinetic drum	Rotation axis	Yaw
(Bonato et al., 2004)	Optokinetic drum	Pictorial realism	Yaw
(Duh et al., 2004)	Optokinetic drum	Temporal frequency	Yaw
(Bonato et al., 2005)	Optokinetic drum	Optical velocity	Yaw
(J. J. W. Lin et al., 2005)	Driving simulator	Temporal frequency	Linear x-axis + roll
(Bubka et al., 2006)	Optokinetic drum	Optical velocity	Yaw
(Bubka et al., 2007)	CRT	Optical velocity	Linear x-axis

1.5.1 Optical velocity

Hu et al. (1989) exposed participants to optokinetic drum rotation speeds of 15, 30, 60, or 90°/s and found that the number of participants reporting nausea increased with increasing drum speed up to 60°/s. Rotation at 90°/s resulted in a lower number of participants reporting nausea compared with rotation at 60°/s. The increase in reports of nausea with increasing drum speed mirrored an increase in reported vection magnitude. Vection was found to be saturated at 60°/s. Since higher velocities may produce perceived fusion of the stimulus pattern and exceed the capacity of eye movements to maintain an optokinetic

response to the stimulus (e.g. Cheng & Outerbridge, 1975; Van Die & Collewijn, 1986), at 90°/s, participants experienced a severe blurring of the stripes. Vection was also reported to be less compelling at this speed. Hu et al. (1989) concluded that the variation of vection magnitude accounted for the variation in motion sickness experienced. However, the authors failed to report correlation coefficients between individual vection and sickness scores.

As mentioned earlier, Sharkey and McCauley (1991) showed that the level of sickness was affected by the global flow rate. In line with Hu et al.'s (1989) findings, higher global visual flow rates (i.e., higher image velocity) were found to be more provocative than lower flow rates (Sharkey & McCauley, 1991).

In a more recent study, So et al. (2001) investigated linearvection and motion sickness during and after navigating through a Virtual Environment at eight different speeds (3.3, 4.4, 5.9, 7.9, 9.5, 23.6, 29.6, 59.2 m/s) presented via a head-tracked HMD. The participants travelled along a predetermined path (i.e. passive motion), and participants could vary their viewpoint using head movements. To enhance their involvement with the Virtual Environment, participants were asked to move their head sideways every 30 seconds. Motion was predominantly in the fore-and-aft and yaw axes. However, some motion occurred in all six axes the degree to which increased with increasing speed.

It was found that both vection and motion sickness ratings increased with increasing speed from 3.3 to 9.5 m/s. At higher speeds, vection and motion sickness ratings tended to stabilise. Unlike previous studies using optokinetic drums, no decrease in vection was observed at the higher speeds[3]. This can be understood when considering the structure of the visual stimulus. As mentioned earlier, the decrease in vection during optokinetic stimulation at high speeds is

[3] Rather than a decline in vection, Berthoz (2000, p.59) claimed that whilst watching a visual scene (i.e. radial optic flow pattern) that moves very quickly, a perceptual inversion occurs whereby the observer has the impression of being motionless. According to Berthoz, this is a familiar experience to drivers of fast cars and auto-racing champions. Above 200 km/h, instead of feeling that they are gaining on the cars in front of them, they suddenly have the extraordinary conviction that the cars in front are approaching them. These drivers have lost vection and have the illusion that they are motionless before a world that is hurtling towards them. Surprisingly, Berthoz did not provide a reference for this previously unreported phenomenon. However, further investigation by the author indicated that this phenomenon is unknown to, at least Scottish, formula-one drivers. (D.M. Coulthard, personal communication, May 2005).

generally attributed to the reduced gain in optokinetic nystagmus causing the image to blur. The stimulus employed by So et al., however, consisted largely of expanding optic flow simulating forward motion which, although known to induce small vergence eye movements (Busettini et al., 1997), does not lead to optokinetic nystagmus as observed during optokinetic drum stimulation. Hence, blurring of the visual image would not be expected to have occurred. Of course, since radial flow patterns become increasingly lamellar towards the periphery (Koenderink, 1986), participants' sideway head movements in So et al.'s study may have induced transient optokinetic nystagmus resulting in blur, particularly at the higher speeds.

The results of So et al. (2001) indicate that navigating a VE at high speeds is likely to increase the level of VIMS. However, the fact that motion took place in several axes, the degree to which furthermore increased with increasing speed, allows for the possibility that the increase in VIMS was not the result of speed *per se*, but rather multi-axis stimulation. Roll motion, for example, increased appreciably with increasing speed. Previously, Kennedy et al. (1996a) have shown that roll motion in particular significantly correlated with the overall level of sickness during flight simulation involving complex motion scenarios. Currently, the effect of multi-axis motion on VIMS is however not well understood. Apart from a number of tilted drum studies (see below), thus far, no studies have specifically addressed this issue.

With regard to vection, So et al. (2001) reported that, on average, the occurrence of motion sickness was preceded by vection which was interpreted as providing support for the idea that vection is a causative factor in VIMS. However, the authors did not report correlation coefficients between individual vection and sickness scores to further substantiate this. Furthermore, vection and motion sickness were assessed at 5-minute intervals only. Both vection and motion sickness are known to occur at much shorter time scales, and have the tendency to wax and wane over time. Hence, the study would have benefited form a higher sampling frequency to allow for a more precise temporal analysis of vection and VIMS.

Bubka et al. (2006) investigated the effect of changes in rotation velocity. Participants viewed the inside of an optokinetic drum rotating at a constant

speed of 30° or 60°/s. In a third condition, drum speed alternated every 30 seconds between 30° and 60°/s. After 30 seconds, participants were asked to close their eyes for 5 seconds during which the drum speed was adjusted. Although speed remained constant in the other conditions, the same procedure was employed to control for exposure duration. Highest sickness scores were observed in the varying speed condition, followed by the 60° and 30°/s, respectively. Significant differences were observed between the varying speed and 30°/s constant speed condition only. Thus, intermittently changing drum speed significantly exacerbated the level of VIMS. Based on the neural mismatch theory, Bubka et al. (2006) argued that at 30°/s the vestibular and visual inputs came to be increasingly more in agreement as vection magnitude became steadier[4]. However, when the 60°/s flow pattern was subsequently viewed, the lack of agreement between vestibular and visual inputs suddenly increased as vection accelerated in response to the faster moving optical flow pattern. Although neural mismatch would be expected to have occurred during the 30° and 60°/s conditions, the degree of conflict in these conditions would be less compared with the intermittently changing condition.

Velocity is defined as the rate of change of position and, thus, refers to both speed and direction. Whereas above studies focussed on the effect of speed on VIMS, Bonato et al. (2005) investigated the effects of change in rotation direction. Participants viewed the interior of an optokinetic drum that rotated at 30°/s. They were instructed to close their eyes and the motor was turned on until the drum steadily rotated. For the first 30 seconds of each trial the participant viewed the drum as it rotated clockwise. In the two experimental conditions, the participant was then instructed to close his/her eyes and the drum was stopped. The motor driving the optokinetic drum was then turned on again causing the drum to rotate either in the same direction (same direction condition) or the opposite direction (different direction condition). After a second viewing interval of 30 seconds, the participants were again instructed to close their eyes for a 5-second period. This cycle was repeated in the same direction condition and the different direction conditions until the end of each trial. A further control condition was employed in which participants viewed the interior

[4] Note that in this study no vection measures were actually obtained.

of the drum rotating at a constant speed. The change in rotation direction led to significant higher levels of VIMS compared with the other conditions. The authors explained their results by arguing that in the changing direction condition visual-vestibular conflict was continuously renewed. This can also be assumed to have happened in the same direction condition, albeit to a lesser extent. It was argued that after participants closed their eyes, vection would decelerate. Upon opening their eyes and viewing the drum rotating in the same direction as before, vection is unlikely to build up all over again. Whereas a period of vection acceleration may take place, it will not be as long as when the trial first began, as was indeed shown in a previous study (Bonato & Bubka, 2004). Based on the neural mismatch theory, the largest degree of conflict may therefore have occurred in the different direction condition.

The aforementioned studies by Bonato and colleagues (Bonato, 2006; Bubka et al., 2006) were partly motivated by Bles et al.'s (1998) criticism regarding the nauseogenicity of optokinetic drum stimulation. Since rotation around the Earth-vertical axis is not expected to lead to motion sickness according to the Subjective Vertical-conflict model, Bles et al. argued that the frequently reported occurrence of VIMS following such stimulation may be due to incorrect alignment of the optokinetic drum. Aware of this criticism, Bonato and colleagues paid special attention to ensure correct alignment of the drum and observer's head position. The finding that changes in both direction (Bonato, 2006) and speed (Bubka et al., 2006) nevertheless increased the nauseogenicity of the optokinetic drum stimulation are difficult to reconcile with the Subjective Vertical-conflict model. However, although care was taken to correctly align the optokinetic drum, participants in both Bonato et al.'s and Bubka et al.'s study adopted an unusual posture, i.e., leaning forward and extending their neck in order to rest their chin on the head/chin rest. This in turn may have had some consequences with regard to the determination of the subjective vertical (J.E. Bos, personal communication, July 2006). Hitherto, no experiments have however been conducted to investigate if and to what extent subtle differences in posture affect the occurrence of VIMS.

As mentioned before, the vast majority of studies into the effect of visual stimulus characteristics have been limited to angular motion. Only recently

random dot optic flow patterns have been used simulating linear motion in the fore-and-aft axis. Bubka et al. (2007) compared the difference in nauseogenicity between an expanding and contracting optic flow patterns simulating forward and backward motion, respectively. Based on the premise that forward motion is far more common than backward motion in normal life, expanding optic flow was hypothesises to result in higher levels of VIMS. Their results showed that this was indeed the case. The authors argued that the fact that we have extensive experience of what should be the appropriate visual-vestibular pairing under expanding optic flow conditions, the discrepancy between expected and sensed motion cues would be greater, resulting in a more salient sensory conflict. Interestingly, although vection was not assessed in Bubka et al.'s study, earlier studies by Berthoz (1975) have shown that during exposure to contracting optic flow patterns (backward motion) vection is experienced as more compelling. This suggests that optic flow patterns inducing a stronger feeling of vection may not necessarily be more provocative.

1.5.2 Spatial frequency

Hu et al. (1997) investigated the effect of spatial frequency by covering the inside of an optokinetic drum with 6,12, 24, 48, and 96 pairs of black and white stripes whilst keeping rotation speed constant at 60°/s. It was found that the intermediate spatial frequency of 24 stripes caused maximum VIMS, vection, and highest frequency of nystagmus. Based on these results, Hu et al. argued that the maximum vection in this condition was also responsible for the fact that this condition also led to the highest level of VIMS. According to the authors, vection reflects the degree of sensory conflict between the visual and vestibular system. It was however also found that several participants reported strong vection but no concomitant VIMS, whereas some participants reported only mild vection but nevertheless reported high levels of VIMS. Again, however, there were no correlations presented of individual motion sickness and vection scores.

The observation that the intermediate spatial frequency also led to the highest frequency of nystagmus was interpreted as providing some support for

Ebenholtz et al's (1994) eye movement hypothesis. Quarck (2000) pointed out that this correlation does not necessarily imply a causal relationship. With regard to sensory conflict, a change of stimulation parameters is enough to account for a change in occurrence of motion sickness. Thus, varying the spatial frequency of the stripes on the rotating drum can modify both the frequency of nystagmus and the intensity of motion sickness by independent pathways. Arising from the same cause, i.e. variation of the visual stimulation, these two variables can be correlated although there is no causal relation between the two (Quarck et al., 2000). As mentioned earlier, Quarck failed to find a relationship between motion sickness and nystagmus using a constant stimulus.

Webb and Griffin (2003) measured vection magnitude and VIMS using two different displays presented via a HMD. Participants either viewed a single dot or five horizontal rows of dots continuously moving from left to right at a constant speed. To ensure that foveal stimulation was identical under both conditions, in the single dot condition, participants were asked to track the dot continuously as it moved from left to right and jumped back to its starting position. In the multiple dot condition, participants were asked to track each dot in the middle row as it passed. Although participants reported more vection in the multiple dot condition, the level of VIMS did not differ significantly between the two conditions. Unlike previous studies, the authors did perform a correlational analysis of the vection and VIMS scores, and this showed no significant correlation between the two. The authors concluded that vection is not a primary cause of VIMS. In addition, it was hypothesised that vection is influenced by peripheral vision, whereas VIMS is influenced by foveal visual stimulation. There are however a number of reasons to question the authors' conclusions. As mentioned earlier, there are strong implications that central and peripheral stimulation yield comparable effects with regard to vection when they are equated for retinal area and specify a background surface (Howard & Heckmann, 1989; Telford & Frost, 1993). In addition, the stimuli employed by Webb and Griffin were only mildly provocative. Since range restriction or lack of variability in criterion scores is known to deflate correlations (Kennedy et al.,

1990a), the failure to find a correlation between vection and VIMS should therefore be treated with caution.

1.5.3 Pictorial realism

Kennedy et al. (2001b) investigated the effect of pictorial/scene realism on vection and VIMS by covering the inside of an optokinetic drum with patterns that were believed to be more realistic than the vertical black-and-white stripes commonly used. One of four different patterns of wallpaper were used which depicted real imagery of more naturalistic stimuli (i.e. waves, clouds, woods, and dots). The different patterns had no effect on either latency, saturation, or magnitude estimation of vection. However, VIMS was found to differ significantly between the different patterns. VIMS was moderate with wood panelling and waves, much greater with clouds, and negligible with dots. It was suggested by the authors that the use of abstract stimuli would reduce the likelihood of VIMS occuring whilst preserving the realistic perception of self-motion. However, it should be noted that, with regard to self-motion perception, Kennedy et al.'s findings are at variance with findings by others. For example, Riecke et al. (2006) recently demonstrated that abstract visual stimuli (e.g. random dot patterns) are actually less effective in inducing self-motion than naturalistic visual stimuli.

Bonato et al. (2004) compared the level of VIMS during optokinetic drum rotation with the inside wall covered with 1) alternating black-and-white stripes, 2) grey stripes having different luminance values, and 3) chromatic stripes (white, red, yellow, black, green, and blue) that approximately matched the luminance values of the stripes in the grey condition. The chromatic condition was found to result in significant shorter onset times and higher sickness scores compared with the other conditions with the inside wall covered in black-and-white or grey stripes. In a separate experiment using the same experimental set-up, Bonato and Bubka (2006) found that chromaticity not only affected the level of VIMS, but also led to faster vection onset times and to a more compelling feeling of vection. In trying to find an explanation for their findings, Bonato and co-workers argued that chromaticity may affect how much an

observer's visual environment appears to be stationary, perhaps because chromaticity is such a common feature of the stationary environment in which the visual system evolved. Bonato et al. (Bonato et al., 2004; Bonato & Bubka; 2006) argued that this may have increased the disparity between visual and vestibular inputs resulting in the elevated levels of VIMS observed.

1.5.4 Rotation axis

Previous studies have shown that VIMS can occur in response to image motion in any of the three (yaw, pitch, roll) rotational axes (Cheung et al., 1991; Hu et al., 1997; Kennedy et al., 2001b; Stern et al., 1990). Using a hollow sphere covered with black dots, Cheung et al. (1991) compared VIMS in normal and bilaterally labyrinthine-defective individuals during visual roll, pitch, and yaw rotation at three different speeds (30, 45, 60°/s). Corroborating the idea that an intact vestibular system is a prerequisite for motion sickness to occur, none of the labyrinthine-defectives reported VIMS, whereas normal individuals reported VIMS during rotation in all three axes. In Cheung et al.'s study, differences in nauseogenicity between the different axes were not considered, possibly because no significant differences were observed. However, according to the sensory conflict theory, the added mismatch between the visual and vestibular vertical during both pitch and roll motion would be expected to lead to higher levels of VIMS. However, the raw data (averaged across the different speeds) was reanalysed by the author and this showed that pitch motion was most provocative, followed by yaw rather than roll motion.

Coincidentally, in the same year, Tiande and Jingshen (1991) published a similar study with the express purpose of comparing the nauseogenicity of pitch, roll, and yaw rotation (45°/s). In line with the sensory conflict theory, pitch motion was found to be most provocative followed by roll and yaw motion. Vection, on the other hand, was perceived as most compelling during yaw motion, followed by roll and pitch motion. During vection about the earth-vertical axis there is only a rotatory component. Predicated on the assumption that the sphere or optokinetic drum is correctly aligned, during yaw vection at constant velocity there is little or no visual-vestibular conflict present after the endolymph

within the semicircular canals have returned to their resting position. For true motion about a horizontal axis, on the other hand, the otoliths continuously signal a rotating gravitational vector, even after the canals have ceased to respond. Therefore, during roll and pitch motion there is a continuous conflict between visual and (expected) vestibular signals. According to the otolith-restraint hypothesis (Held et al., 1975), pitch and roll vection should be weaker than yaw vection. This was indeed seen as also previously shown by others (A. Howard et al., 1988). Otolith restraint also accounts for the limited sense of illusory self-tilt that accompanies pitch and roll vection. As previously suggested by Howard et al. (1988), based on the fact that we execute pitch movements of our heads more frequently than roll movements, pitch vection would be more restrained by the otolith organs and therefore weaker than roll vection. Since more severe restraint generates more severe conflict, it can be thus be expected that pitch vection is more provocative than roll vection, which in turn is more provocative than yaw vection.

Lo and So (2001) also compared the level of VIMS as a result of pitch, roll, and yaw motion, in a study similar to that of Tiande and Jingshen's (1991). In order to compare the effect of scene motion as such, a control condition was added in which participants viewed a static image. Unlike the studies mentioned above which used stimuli rotating at a constant velocity, Lo and So exposed individuals to oscillating motion at a speed of 30°/s with a peak-to-peak amplitude of 120°. As a consequence, oscillation about the Earth-vertical axis (yaw) was expected to result in a significant increase in VIMS. The additional mismatch between the visual and vestibular vertical during both pitch and roll oscillation was expected to exacerbate the level of VIMS in comparison to yaw oscillation. Not surprisingly, scene oscillation in all three axes led to a significant increase compared with the static condition. However, no significant differences were observed between the three different rotational axes. However, there was a clear trend in the predicted direction in that VIMS was higher in both roll and pitch oscillation. Unlike Tiande and Jingshen's (1991) findings, roll oscillation was slightly more provocative than pitch oscillation. These discrepancies may be partly explained by the fact that the stimuli in Lo and So's (2001) study were presented via an HMD providing a restricted visual field of view of 48° horizontal

x 36° vertical. As a consequence, participants suffered only mild symptoms. Full field stimulation as in Tiande and Jingshen's study may have provided a more provocative stimulus amplifying the effect of the experimental manipulation.

Lo and So interpreted the elevated level of VIMS following scene oscillation as evidence that VIMS is a type of vection induced motion sickness. However, although vection was presumed to have occurred, no data were actually obtained to support this. This is particularly unfortunate considering Tiande and Jingshen's finding that vection of a lesser strength (pitch and roll) may be more provocative than a more compelling feeling of vection (yaw). In other words, vection may indeed be a necessary condition for VIMS to occur as suggested by Hettinger et al. (1990), but the level of sensory mismatch does not appear to be reflected in the degree of vection (cf. Hu et al., 1997).

Similar conclusions can be drawn from optokinetic drum studies in which the orientation of the stripes has been systematically altered. In a study by Andre et al. (1996), observers were exposed to 60°/s optokinetic drum stimulation with the inner wall of the optokinetic drum covered by either vertical stripes or off-vertical stripes tilted 15° in the direction of drum movement. Under the tilted drum condition, in which the stripes moved down and to the right, participants reported complex vection with both a horizontal and vertical component (barber pole). As predicted, the added mismatch between the visual vertical and the vestibular vertical in the tilted condition significantly increased gastric tachyarrhythmic activity, a measure repeatedly been shown to be associated with the occurrence of motion sickness (Koch et al., 1990; Xu et al., 1993). However, no significant differences were found in subjective measures of VIMS. Vection was reported to be less compelling in the tilted condition. More recently, Bubka and Bonato (2003) conducted a similar experiment in which observers were exposed to 60°/s optokinetic drum stimulation with the drum either aligned to the earth-vertical axis (yaw), or tilted relative to the axis of rotation (5° and 10° tilt). In this study, increased drum tilt was found to significantly increase the level of VIMS. Although vection was not assessed in this study, a follow-up study indicated no significant differences in vection (F. Bonato, personal communication, September 2007). Taken together, these findings also suggest that the level of sensory mismatch is not reflected in the degree of vection.

The titled drum studies (Andre et al., 1996; Bubka & Bonato, 2003) further illustrate the difficulty in testing the Subjective Vertical-conflict model (Bles et al., 1998). Under most circumstances in which a vertical mismatch occurs, there is also a conflict between sensed and expected motion. Following the neural mismatch theory, the increased nauseogenicity during drum tilt can be explained by the introduction of a wobbling (sway) component that would normally be accompanied by otolith stimulation. At the same time, the increased nauseogenicity can be equally explained by the difference between the sensed and subjective or expected vertical.

1.5.4 Temporal frequency

With regard to the nauseogenicity of real motion, it is known that the important physical characteristics include the frequency, and less reliably, the acceleration and amplitude of the motion (Griffin, 1990; Guignard & McCauley, 1990). In laboratory studies using linear and angular oscillation, motion sickness peaks at a frequency of approximately 0.2 Hz, whereas motion at other frequencies produces little or no sickness (Bos & Bles, 1998; Donohew & Griffin, 2004; Golding & Markey, 1996; Golding et al., 2001; Griffin, 1990; Guignard & McCauley, 1990). This frequency range is consistent with what is known about the provocative motion profiles of transport systems associated with motion sickness including ships, trains, aircraft, and cars (Guignard & McCauley, 1990; Lawther & Griffin, 1988).

It has been suggested that the predominant frequency of oscillation of a visual display also plays an important role in the generation of visually induced motion sickness (Kennedy et al., 1996a), and that, similar to true motion sickness, imposed visual motion at a frequency around 0.2 Hz is most provocative (Hettinger et al., 1990). Besides the known provocative frequency range with regard to true motion sickness, this latter hypothesis was based on the observation that visual stimuli below 0.5 Hz led to higher vection magnitudes (Post et al., 1989), that vection magnitude induced by dynamic rod and frame stimuli (i.e., visual roll motion) was found to be highest at 0.213Hz within the

frequency range of 0.013 Hz to 0.213 Hz[5] (Babler & Ebenholtz, 1989), as well as the finding that the VOR approaches unity gain and zero phase lag at around 0.2 to 0.25 Hz and higher (Paige, 1989). However, there appears to be no published data to substantiate this specific frequency dependence of visually induced motion sickness. Furthermore, Hettinger et al. (1990) failed to elaborate on the question of why oscillating motion at a frequency around 0.2 Hz would be most provocative.

Recently, Parker and co-workers (Duh et al., 2004; Lin et al., 2005; Parker et al., 2001) hypothesised visually induced motion sickness to peak around the frequency where the summed response of the visual and vestibular self-motion systems is maximal. In order to determine this so-called "crossover frequency", Duh et al. (2004) examined the frequency response of the visual self-motion system by assessing postural sway in response to visual scene roll oscillation (0.8, 0.4, 0.2, 0.1, 0.05 Hz) with peak scene velocity held constant across frequencies at 70°/s. Stimuli were presented via either HMD or vision dome. The results showed similar low-pass filter characteristics as previously reported for both linear and angular motion (Berthoz et al., 1979; Wong & Frost, 1978) with the system's response inversely related to the frequency of scene oscillation (see figure 1.6a). Interestingly, these data show a remarkably consistent pattern in the visual self-motion frequency response despite the wide variety of motion profiles (e.g. acceleration, amplitude, velocity, motion axis) and dependent variables (i.e. postural sway, vection velocity and magnitude) employed.

By plotting the high-pass vestibular frequency response curve based on data from Melvill Jones & Milsum (1965), the crossover frequency was subsequently determined by Duh et al. (2004) to be around 0.06 Hz (see figure 1.6b). Since both systems would provide strong signals at this frequency, they argued that conflicting visual and vestibular self-motion cues at this frequency would be most provocative.

[5] Note that this may represent a ceiling effect considering the restricted frequency range investigated.

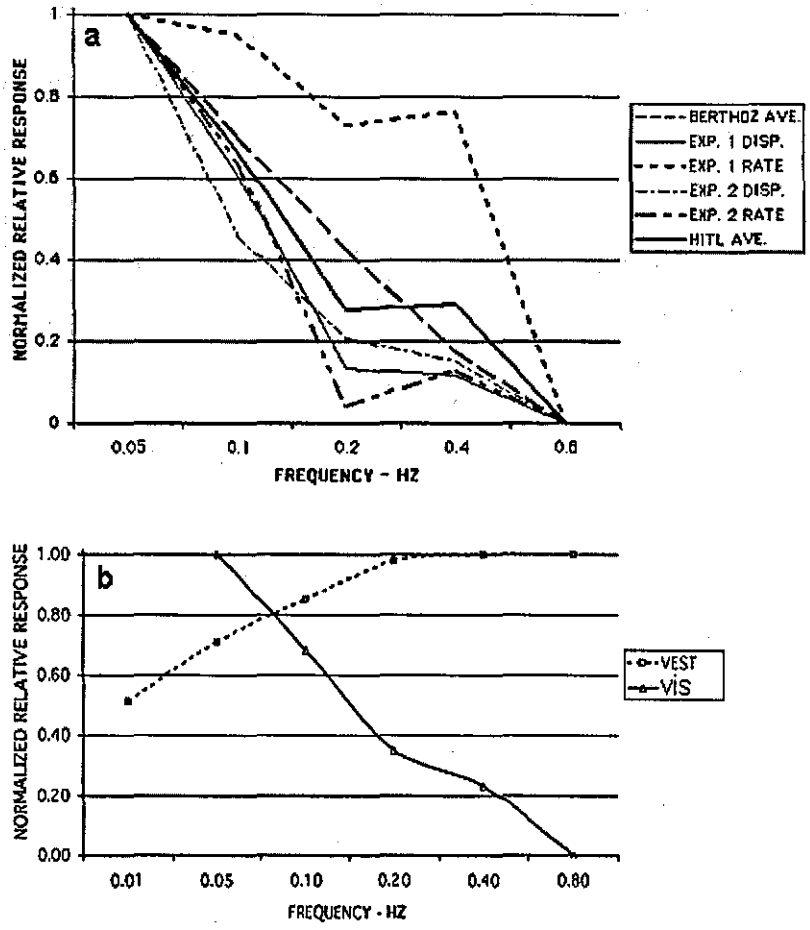


Fig 1.6 (a) Postural instability (Disp.) and perceived difficulty maintaining upright posture (Rate) as a function of visual stimulus frequency. Exp. 1 Disp.: centre of balance dispersion from Experiment 1; Exp. 1 Rate: subjective difficulty rating from experiment 1; Exp. 2 Disp.: dispersion from experiment 2; Exp. 2 Rate: difficulty rating from experiment 2. HITL Ave.: combined average dispersion and rating data from Experiments 1 and 2. Berthoz Ave.: combined average self-motion perception frequency responses from three experiments cited by Berthoz et al. (1979).

(b) Visual-vestibular crossover. VIS: combined HITL Ave. and Berthoz Ave. Vest: vestibular frequency response. The crossover frequency, the frequency at which the summed gain from the visual and vestibular self-motion systems is maximum, appears to be about 0.06 Hz (from Duh et al., 2004).

It should be noted that it is not completely clear why the crossover frequency was determined at 0.06 Hz. Inspection of figure 1.6b would suggest the crossover frequency to be closer to 0.08 than 0.06 Hz. A more fundamental problem with the determination of the crossover frequency, however, is the use of normalised data. This becomes clear when one considers the situation had the visual system's response been investigated at frequencies below 0.05 Hz. Predicated on extrapolation of the visual system's response curve, one would suppose that the maximum response may not be at 0.05 Hz. If so, then

normalisation of the data to a lower frequency would have resulted in a more gentle slope of this curve. Subsequently, the crossover frequency would have shifted towards the lower frequency range.

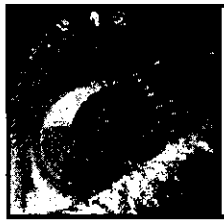
A second problem with the determination of a crossover frequency using normalised data is that it does not allow for unequal weighting of the visual and vestibular signals. In terms of sensory conflict, equality of weighting is implicit in the analysis, but a normalised response of 0.5 for the vestibular system is unlikely to be directly comparable to a normalised response of 0.5 for the visual system. Thus, although the concept of a crossover frequency at which sensory conflict would be maximal is reasonable, determination of this frequency on the basis of normalised data is questionable.

To test the crossover hypothesis, Duh et al. (2004) conducted an experiment in which subjects were exposed to concurrent visual and inertial yaw oscillations at slightly different frequencies (beat frequencies). The results showed that, as predicted, motion sickness was indeed more readily evoked around the crossover frequency than at a higher frequency (0.2 Hz). Further support for this hypothesis was recently provided in a study by Lin et al. (2005) in which stationary observers were exposed to optic flow patterns simulating constant velocity linear motion in the fore-and-aft axis combined with oscillating roll motion at three different frequencies, 0.035, 0.080, and 0.213 Hz, with a peak-to-peak amplitude of 120°. As predicted by the crossover hypothesis, motion sickness was found to be highest at the mid-frequency range, i.e., 0.080 Hz. Taken together, these results suggest that the crossover hypothesis may not only hold under conditions of concurrent visual and vestibular stimulation, but also during visual stimulation in the absence of vestibular stimulation such as typically occurs in fixed-base simulators and other VR systems.

1.5.5 Summary

Previous studies into the effect of visual stimulus characteristics on VIMS have been mainly limited to rotation about the Earth-vertical axis. It was already mentioned in the introduction that in both real and simulated environments rotation has only a limited role in the normal locomotion of the human observer.

The principal motion components that occur during normal locomotion of a person are translations and, more specifically, translation along the line of sight in the forward direction. However, except for a recent study by Bubka et al. (2007), no systematic studies have however been conducted with regard to linear motion. Hence, the aim of the experimental work described in the following chapters is to investigate VIMS during simulated motion in the fore-and-aft axis. In addition, systematic investigation of both the time course and magnitude of vection is expected to elucidate the relationship between vection and VIMS.



C_2
Methods

2.1 Summary

This chapter describes the methods used in the experimental work described in the following chapters. The experimental setup including the apparatus and visual stimuli will be described first. This is followed by a description of the different motion sickness and vection measures taken.

2.2 Apparatus and stimuli

The physical layout of the VISERG Vision Lab is illustrated in figure 2.1a. Figure 2.1b shows a participant in the experimental setup. Participants were seated on a stationary chair with backrest. The head of each participant was stabilised by means of a head/chin rest with their arms resting on a custom-made table (85(h) x 80(w) x 40(d) cm). They faced a wide-angle rectangular screen (Da-Tex (rear), Da-Lite Screen Company, Inc. Dimensions: 173 x 234 cm) that was centred at the midpoint between the participant's eyes. The viewing distance was 80 cm. Although the lab was light-tight with regards to the exterior, to prevent any stray light caused by equipment reaching the participant's area, black curtains were hung down from the ceiling on both sides of the screen creating a viewing booth.

To occlude the edges of the screen and other peripheral features, participants wore goggles with the glasses removed. The goggles limited the visual field to 65° (horizontal) x 59° (vertical) of angle. Acoustic localisation cues were masked by pink noise (75 dB) transmitted to earphones worn by the participant. In addition, auditory alerting bleeps of different frequencies (500, 750, and 1000 Hz at 100 dB) were played at random intervals throughout the exposure duration. Communication with the participants during exposure was via a microphone. To monitor participant's well being and to ensure compliance with

instructions, an infrared camera was placed on the side (see figure 2.1a) pointing towards the participant's face and relaying images to a monitor outside the viewing booth (M2 in figure 2.1a).

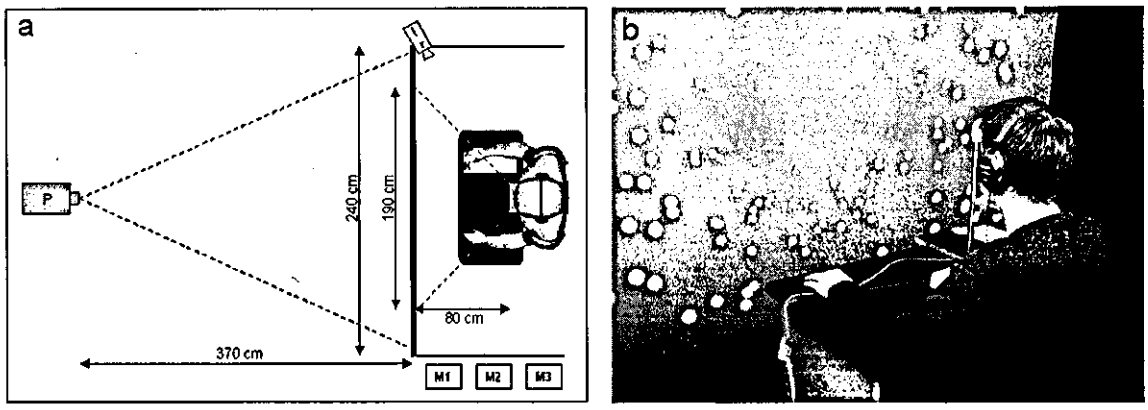


Fig. 2.1 (a) Physical layout of the Vision Lab. P: projector; IR: infrared camera; K: keyboard; M1: stimulus generating computer; M2: monitor displaying infrared camera image; M3: vection data acquisition computer. (b) A participant shown in front of the back-projection screen.

The visual stimuli were produced using Matlab (version 6.5; Cogent Graphics Toolbox) controlling a Matrox Millennium P750 graphics card (64Mb) running on a DELL GX computer. All stimuli were presented at a refresh rate of 60 Hz and were backprojected onto the screen with a Hitachi CP-X958W/E projector (1024 x 768 pixels). The visual stimuli consisted of 500 moving white filled-in circles (10.82 cd/m^2) on a black background (0.35 cd/m^2). The projected motions in the display were geometrically correct projections of rigid motion along the fore-and-aft (x) axis. Dot velocity and size varied exponentially as a function of their simulated location in depth (Andersen & Braunstein, 1985). Dot size at the eye ranged from 0.22° at the middle to 2.97° at the periphery. Radially expanding/contracting dot motion simulated forward/backward linear motion in the fore-and-aft (x) axis through an area uniformly filled cloud of randomly positioned dots. Displaying dots in the centre of the display created a jittering effect creating a disruption in the continuity of the elements in simulated space negatively affecting the perception of depth. To avoid this problem, it was decided not to display any dots at the very centre of the visual scene. As a consequence, there was a black disc subtending 8.75° of visual angle (figure

2.2). A red (fixation) dot (0.57° of visual angle) was projected at eye height in the centre of the screen.

The spatial frequency of the stimulus was determined employing the method developed by So et al. (2001). This method calculates the dominant spatial frequency of a row/column within the visual scene. In order to do so, a numerical value of each pixel with regard to its luminance information (i.e. greyscale) is extracted. The power spectral density of this greyscale series is then calculated using the Fast Fourier Transform (FFT) operation resulting in the spatial frequency power spectral density (SFPSD). Following the "combined method" (see So et al. (2001) for further details), the average dominant frequency is determined. Repeating this procedure for each individual row and column allows for the calculation of the average vertical and horizontal spatial frequency (SF_{vert} and SF_{horiz}, respectively) in cycles per degree (cpd). The radial spatial frequency (SF_{rad}) is finally obtained by calculating the geometrical mean of SF_{vert} and SF_{horiz}. Following this method, the spatial frequencies for the current stimulus are: SF_{vert} = 0.259 cpd; SF_{horiz} = 0.267 cpd; SF_{rad} = 0.372 cpd.

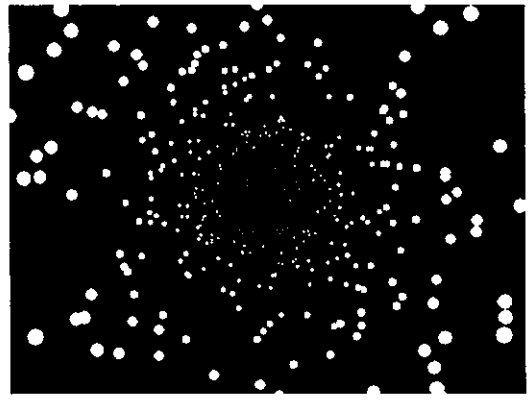


Fig. 2.2 Sample frame of the optic flow pattern.

2.3 Measures

This section gives details on the scales that were used in the experimental studies for participants to report their level of motion sickness, perception of self-motion (vection), and previous susceptibility to motion sickness.

2.3.1 Revised Motion Sickness Susceptibility Questionnaire (MSSQ)

Before commencing an experiment, participants were asked to complete the revised Motion Sickness Susceptibility Questionnaire (MSSQ) (Golding, 1998). The MSSQ, shown in appendix 1, is a two-section questionnaire used for the assessment of motion sickness history. The questionnaire asks for previous sickness occurrences in cars, busses, trains, aircraft, small boats, large ships, swings, merry-go rounds, and leisure park attractions for ages up to 12 (MSSQ-A), as well as for the past 12 years (MSSQ-B). The occurrence of nausea and vomiting, corrected for reported travel experience, are used to establish an index of susceptibility. This results in a single MSSQ raw score (MSSQ-AB) ranging from 0 to 190, with the 50th percentile of a normal population reached at MSSQ 37. In addition, the MSSQ includes a single-item susceptibility question which reads as follows: "Do you regard yourself susceptible to motion sickness?"; answer categories: "Not at all", "Slightly", "Moderately", and "Very much so".

2.3.2 Simulator Sickness Questionnaire (SSQ)

The SSQ was derived from the Pensacola Motion Sickness Questionnaire (MSQ), which was originally developed to assess motion sickness induced by physically moving environments. Kennedy et al. (1988) conducted a large survey of motion sickness events in US Navy simulators using the MSQ listing a total of 28 symptoms (see table 2.1). Symptoms that showed low response rates or little change from pre exposure to post exposure were later discarded and a total of 16 items were retained to make up the SSQ (in table 2.1, symptoms included in the SSQ are indicated by an asterisk) (Kennedy et al., 1993).

Based on the results from a factor analysis, three symptom clusters were identified which were used as the basis for three SSQ subscales which were subsequently labelled as Nausea (N), Oculomotor (O), and Disorientation (D) (Kennedy et al., 1993). Due to shared variance between symptoms, some of the symptoms belong to two clusters as shown in table 2.2.

TABLE 2.1 SYMPTOMS IN MSQ AND SSQ (*)

1. General discomfort *	11. Nausea *	20. Faintness
2. Fatigue *	12. Difficulty concentrating *	21. Awareness of breathing
3. Boredom	13. Mental depression	22. Stomach awareness *
4. Drowsiness	14. Fullness of head *	23. Decreased appetite
5. Headache *	15. Blurred vision *	24. Increased appetite
6. Eyestrain *	16. Dizzy (eyes open) *	25. Desire to move bowels
7. Difficulty focussing *	17. Dizzy (eyes closed) *	26. Confusion
8. Increased salivation *	18. Vertigo *	27. Burping *
9. Decreased salivation	19. Visual flashbacks	28. Vomiting
10. Sweating *		

Symptoms are scored on a four-point scale (0 = absent, 1 = slight, 2 = moderate, 3 = severe) and are then added within each cluster. By multiplying the sum total of each cluster with a cluster specific weight factor, three subscale scores can be calculated. A total sickness score can be derived by adding the three clusters together and multiplying this score by a weighting factor of 3.74. The SSQ symptoms, clusters and weighting factors are summarised in table 2.2.

TABLE 2.2 SSQ SYMPTOMS, CLUSTERS, AND WEIGHTING FACTORS

	Clusters		
	N	O	D
General discomfort	•	•	
Fatigue		•	
Headache		•	
Eyestrain		•	
Difficulty focussing		•	•
Increased salivation	•		
Sweating	•		
Nausea	•		•
Difficulty concentrating	•	•	
Fullness of head			•
Blurred vision		•	•
Dizzy (eyes open)			•
Dizzy (eyes closed)			•
Vertigo			•
Stomach awareness	•		
Burping	•		
Total	(A)	(B)	(C)

N-score = (A) x 9.54
O-score = (B) x 7.58
D-score = (C) x 13.93
Total sickness score = {(A) + (B) + (C)} x 3.74

Although the SSQ is widely used and is currently the only validated instrument, it has been criticised for a number of reasons. First, it may not always be clear whether the SSQ scores reflect simulator sickness or simulator aftereffects (Lampton et al., 1994). To measure aftereffects, participants need to be explicitly instructed to rate their symptoms as experienced after they have exited the simulator/VR system. Conversely, to assess sickness during exposure, participants need to be instructed to rate their symptoms as they remember them when they were at their worst during exposure. As mentioned by Wertheim (1999), this is rarely spelled out in the literature.

Secondly, the use of SSQ subscales needs to be treated with caution. Clemes (2004) pointed out that naming of clusters can lead to confusion and misinterpretation of what it is actually measuring. Kennedy himself (1993) has contributed to this confusion by stating that "...the three-factor solution suggested the existence of three (partially) independent symptom clusters, each reflecting the impact of simulator exposure on a different "target system" within the human... (p. 208)." However, the name "oculomotor" for example, suggests that this subscale is measuring problems with the oculomotor system, such as changes in heterophoria. Of course, this is not what this subscale is concerned with and the "oculomotor" subscale is presumably measuring symptoms of visual discomfort, even though only three out of the seven symptoms listed in this subscale have anything to do with vision (eyestrain, difficultly focusing and blurred vision). Therefore if an individual reported none of these symptoms, but reported the presence of the other symptoms on this subscale (general discomfort, fatigue, headache, and difficultly concentrating) it would by wrongly assumed that participants were experiencing visual discomfort or problems with their oculomotor system (Clemes, 2004). It should be noted though that the subscale scores can provide useful diagnostic information as to the specific causes of the resulting symptoms (Kennedy et al., 1993). High oculomotor subscale scores caused by excessive report of eyestrain, for example, may be indicative of system calibration imperfections (e.g. inter pupillary distance).

Furthermore, the SSQ scoring system is based on the assumption that all participants are in their normal state of health and symptom free prior to exposure (Kennedy et al., 1993). Consequently, participants reporting

themselves to be 'other than healthy' were not included in the analysis. Although Kennedy et al. (1993) point out that the SSQ is intended for application to post exposure symptoms only and strongly argue against the use of difference scores (post – pre scores), in practice, this requirement is not feasible. In a study by Ramsey (1999), for example, the data from 52% of the sample had to be rejected due to these participants reporting some symptoms on the SSQ administered prior to exposure. Hence, pre-exposure symptom scores were taken into account and the change in symptoms over the exposure duration was used for analysis. It is acknowledged that restricting the scoring range may compromise reliability of these scores.

Notwithstanding the criticism regarding the use and interpretation of the SSQ, it was decided to use the SSQ for two reasons. First, the SSQ is currently the only validated assessment tool (Kennedy & Fowlkes, 1992), and second, the lack of standardisation and arbitrariness with regard to the development of self-styled 'adapted' versions of the SSQ within the field of VIMS makes it difficult to compare results between studies (see also Stanney et al., 1998).

In the studies presented in the following chapters, before and after each session participants were asked to fill out the MSQ. It was decided to use the MSQ rather than the SSQ to allow for the possibility that symptoms excluded in the SSQ may be reported. Analyses were however based on the 16 symptoms that compile the SSQ. The measure of interest was the difference score (post – pre-exposure score). The MSQ is shown in appendix 2.

2.3.3 Motion sickness ratings per-exposure

Since completion of the SSQ is relatively time consuming, it cannot be administered unobtrusively during a session. To capture successive ratings of motion sickness experienced over time, participants rated the severity of their motion sickness at 1-min intervals on Bagshaw and Stott's (1985) four-point rating scale shown in Table 2.3.

TABLE 2.3 4-POINT MOTION SICKNESS RATING SCALE (Bagshaw & Stott, 1985)

Rating	Description
1	No symptoms
2	Mild symptoms, but no nausea
3	Mild nausea
4	Moderate nausea

Experiments were stopped at sickness rating 4 ('moderate nausea') or after 20 min, whichever was the sooner. Participants who reached a sickness rating of 4 and stopped before 20 min were assigned continuation values of 4. The measures of interest were the time for participants to first report a sickness rating of 2 ('time to sickness rating 2') and 3 ('time to sickness rating 3'), the maximum sickness rating, and the sum of the sickness ratings over the 20 min exposure duration ('accumulated sickness rating'). If no symptoms were reported, an accumulated sickness rating and symptom onset time of 21 was recorded.

2.3.4 Vection measures

To ensure participants differentiated between object- and self-motion, they were asked during this briefing to view a vertically translating optic flow pattern (see figure 2.3) until a compelling sensation of vertical linear self-motion was reported. This typically occurred after about 15 seconds. When they indicated that they fully understood the task the experiment commenced.

Fig. 2.3 Sample frame of the vertically translating optic flow pattern.

To evaluate the time course and total duration of vection, participants were instructed to press one of two buttons (depending on the direction of perceived vection, i.e. forward or backward linear vection) on a standard PC keyboard (see figure 2.1a) whenever they experienced vection, and to keep it pressed for as long as they experienced vection.

The keyboard sent a binary signal to a computer and stored for off-line analysis. It is acknowledged that the contrasting perceptual states of object-motion and vection are not mutually exclusive but can perceptually coexist. The perception of self-motion often develops gradually with a simultaneously perceived slowing of object or environment motion (Dichgans & Brandt, 1978). In spite of this gradual build-up, participants were required to decide in a binary manner whether or not they perceived themselves as moving in order to ensure a simple and intuitive task as well as to enable statistical analysis of the perceptual states as a categorical variable.

Vection onset latency was defined as the time it took for participants to first press the key to indicate the occurrence of vection. Vection duration was defined as the percentage of the total exposure time that vection was reported. Since vection may not be experienced continuously ("drop outs"), the latency and duration measures are not completely redundant.

The overall magnitude of perceived vection was measured post-exposure. Participants were asked to rate their experience in terms of the following question: 'Whilst watching the moving images, did you get the feeling of

motion? Did you experience a compelling sensation of self-motion as though you were actually moving?' The endpoints of the 7-point Likert scale were anchored as 'not at all' (1) and 'very much so' (7) (after Prothero, 1998).

Where applicable, participants were asked to rate the vection magnitude of the individual directions that constituted the optic flow pattern using the same 7-point Likert scale. For example, after exposure to oscillating linear motion in the *x*-axis, they were asked to indicate the perceived vection magnitude in the forward and backward direction separately. The questionnaire is given in appendix 3.

C_3
VIMS during constant and varying velocity

3.1 Summary

The functional importance of visual-vestibular interaction during horizontal linear motion is clear because the otoliths only provide information about changing velocities, whereas the visual input contributes supplementary information about constant velocity. According to the neural mismatch theory, it follows that visually induced motion sickness would be expected to occur during varying but not constant velocity visual stimulation. Unlike constant velocity motion, during exposure to motion of varying velocity the self-motion signals detected by the visual system are not corroborated by an anticipated, but absent, vestibular signal. To test this hypothesis, seated participants viewed random-dot optic flow patterns simulating either translational motion at constant velocity in (i) forward and (ii) backward direction, or else sinusoidally oscillating (iii) fore-aft and (iv) roll motion. To provide baseline data, a separate experiment was conducted in which participants viewed a stationary image. Consistent with the neural mismatch theory, motion sickness levels during constant velocity motion did not significantly differ from those observed in the baseline condition, whereas visual roll motion was found to be most provocative. Unexpectedly, however, sinusoidally oscillating motion was only marginally more provocative than constant velocity motion. This raises the question whether visually induced motion sickness is frequency dependent.

3.2 Introduction

Our perception of self-motion is maintained by integrating the signals received from the various motion sensors, predominantly the visual and vestibular system. The necessity of this sensory integration process to maintain a veridical perception of self-motion becomes particularly apparent for pedestrian man, whilst being exposed to unnatural motion patterns. For instance, when a person is physically oscillated back and forth along a linear path in the absence of a visual frame of reference, the person gradually experiences body tilt rather than linear motion. This so-called "somatogravic illusion" stems from the fact that the otoliths do not distinguish translation from tilt (Howard, 1986). Not surprisingly, this illusion is prevented from occurring in the presence of concomitant optic flow information signalling mere translation.

The gradual development of the somatogravic illusion hints at a further limitation of the vestibular system, namely the fact that the vestibular system only provides information about changing velocities, or, stated differently, the system's inability to signal constant velocity motion (Howard, 1986). Whereas the absence of rotational signals from the semicircular canals would initially disambiguate the otolith signal, after a period of steady acceleration, the absence of rotational signals from the canals would no longer contradict the sensation of tilt because, with prolonged tilt, the cupulae would have been restored to their central position.

The significance of sensory integration becomes apparent also when travelling at a constant speed with our eyes closed. Based on the inertia of the fluid in the otoconia of the otolith organs, the otolith system transduces only linear acceleration, so periods of constant velocity cannot be registered by this system. Thus, when moving at constant velocity, visual input is the major source of sensory information that allows the observer to adequately perceive body motion in space.

As evidenced by the fact that we generally do not get motion sick whilst driving on a motorway or riding in a train at a constant speed, motion sickness does not arise due to discrepancies between the messages provided by the different motion sensors, as originally claimed by the "intermodality conflict" hypothesis

(Claremont, 1931, cited in Oman, 1982). As a further example, during rotation about the z-axis for instance, the vestibular and visual responses always differ from one another. These signals are primarily complementary whereby the visual and vestibular systems become increasingly responsive at lower and higher frequencies, respectively (Zacharias & Young, 1981). Subsequent integration in the central nervous system of these different information signals provides a signal that corresponds to the actual stimulus for normal natural movements. Consequently, a correct spatial orientation can be maintained in this manner without motion sickness. Accordingly, Reason (1978) proposed a more elaborate version of the sensory conflict theory, the "neural mismatch" hypothesis, stating that the conflict results from a comparison between actual and *anticipated* sensory signals. Thus, the central tenet of the neural mismatch theory is that motion sickness arises when the sensory organs supply messages different from those expected on the basis of previous experience.

Although it is sometimes argued that visual scene motion with a lack of vestibular signalling at constant velocity generates motion sickness (e.g., Williamson & Stern, 2003), it is clear from the above that under these circumstances one would expect the incoming sensory signals to be consistent with previous sensory experience despite the lack of inertial motion, and hence, little or no motion sickness to occur.

The current study was designed to test the hypothesis that conflict regarding sensed and expected self-motion would affect motion sickness. In the first experiment, seated participants were exposed to radial optic flow patterns simulating observer motion along the fore-and-aft axis at either constant or sinusoidally oscillating velocity. Contrary to constant velocity motion, during exposure to motion of varying velocity the self-motion signals detected by the visual system are not corroborated by an anticipated, but absent, vestibular signal. This latter condition was therefore hypothesised to result in significantly higher levels of motion sickness.

It has previously been suggested that backward motion is more provocative than forward motion (Kolasinski, 1995; McCauley & Sharkey, 1992). Since the varying velocity condition in the current study simulated oscillating forward-

backward motion, the anticipated nauseogenicity of varying velocity motion could be ascribed to the presence of backward motion. To control for the effect of motion direction, participants were exposed to constant velocity in both forward and backward direction.

The predicted absence of visually induced motion sickness after constant velocity motion stimulation, if it occurs, could arguably be explained also by low sample susceptibility, or by mild provocativeness of the apparatus used. Therefore, oscillating visual roll motion was added as a further condition. Besides the absence of appropriate gravitational acceleration cues detected by the otoliths, an additional semicircular canal-visual mismatch occurs during visual roll motion, which would be expected to induce clear symptoms, and thus this condition acted as a control.

Previous studies (Flanagan et al., 2004; Lo & So, 2001) have shown that even in the absence of visual scene motion a certain increase in symptoms can be expected in experiments like ours. Therefore, baseline data were collected in a second experiment in which participants viewed a single stationary frame of the optic flow pattern under otherwise identical conditions.

An additional aim of this study was to investigate the relationship between visually induced motion sickness and vection. Although visually induced motion sickness is often referred to as "vection induced motion sickness" (Bubka & Bonato, 2003; Hu et al., 1997; Hu & Stern, 1998; Levine et al., 2003; Reid et al., 1995), contradictory results are found in the literature as to the role of vection in the generation of the symptoms. Whereas some authors suggest vection to be a necessary condition for motion sickness to occur (Hettinger et al., 1990; Hettinger & Riccio, 1992), others have failed to find a relationship between vection and visually induced motion sickness (Webb & Griffin, 2002, 2003). To gain a better understanding of the relationship between vection and motion sickness, apart from its occurrence, the time course of vection was investigated in relation to the development of motion sickness.

3.3 Methods

Participants

Twelve healthy participants (ten male and two females) with a mean (± SD) age of 28.6 (± 5.7) years, gave their informed consent to participate in the study, following its approval by the Loughborough University Ethical Advisory Committee. All participants had intact vestibular function, were not receiving any medication, and had normal or corrected-to-normal vision. Using the revised version of the Motion Sickness Susceptibility Questionnaire (MSSQ) (Golding, 1998), the mean percentile score for the participants in this study was 63%, indicating the sample to be slightly more susceptible to motion sickness than the normal population.

Apparatus and stimuli

The stimuli were generated in real time with a frame rate of 60 Hz using Matlab (version 6.5) running on a DELL GX computer fitted with a Matrox Millenium P750 graphics card (64Mb). The images were backprojected onto a tangent screen (190 cm x 145 cm) with a Hitachi CP-X958W/E projector (1024 x 768 pixels). The display consisted of 500 white dots with a luminance of 10.82 cd/m^2 randomly positioned on a black background of 0.35 cd/m^2 (Michelson contrast ratio of 0.94). Dot velocity and size varied exponentially as a function of their simulated location in depth. Dot size at the eye ranged from 0.22° at the middle to 2.97° at the periphery. For technical reasons, there were no dots at the very centre of the visual scene, and as a consequence, there was a black disc subtending 8.75° of visual angle (see figure 2.2 for a sample frame of the stimulus).

All participants were exposed to four conditions. Conditions F (forward) and B (backward) simulated motion along the fore-aft axis at constant velocity (average optical velocity 26°/sec). In condition FB, sinusoidally oscillating motion along the fore-aft axis was simulated (0.025 Hz; average optical peak

velocity 26°/sec). Condition R simulated oscillating roll motion around the fore-aft axis (0.125 Hz; average optical velocity of 30°/sec, peak-to-peak amplitude of 120° (± 60°)). See appendix 28 for a more detailed description of the visual stimuli.

To control for eye movements, participants were instructed to fixate a red dot (0.57° of visual angle) projected at eye height in the centre of the screen. Participants each viewed the moving displays binocularly from a fixed viewpoint with their head held in position by a head/chinrest at a distance of 90 cm from the screen. To occlude the edges of the screen and other peripheral features, participants wore goggles, which limited their visual field to 65° (h) x 59° (v) of visual angle. Acoustic localisation cues were masked by white noise (75 dB) transmitted to earphones worn by the participant. Communication with the participants during exposure was via a microphone.

Design

A repeated measures design was used with each participant acting as his/her own control. The order in which the 4 conditions were presented was balanced using a 4 x 4 balanced Latin square design, to minimise order effects. Each exposure took 20 minutes and was separated by at least 24 hours in an attempt to limit any bias caused by habituation to the stimulus.

Motion sickness measures

Before and after each session, the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) was completed by each participant. The measure of interest was the change in the SSQ total scores (post – pre exposure score). In addition, participants rated the severity of their motion sickness every minute on Bagshaw and Stott's (1985) malaise scale. The experiment was stopped at sickness rating 4 ('moderate nausea') or after 20 minutes, whichever was the sooner. Participants who reached a sickness rating of 4 and stopped before 20 minutes were assigned continuation values of 4. The measures of interest were

the time for participants to first report a sickness rating of two and three ('time to sickness rating 2 and 3', respectively), and the sum of the sickness ratings over the 20 minutes exposure duration ('accumulated sickness rating'). If no symptoms were reported, an accumulated sickness rating and symptom onset time of 21 was recorded.

Vection measures

Vection was defined as a compelling feeling of self-motion, such as "the feeling you get when a train moves next to you and you mistake it for your own motion." To ensure participants differentiated between object- and self-motion, before the first session began they were exposed to the roll motion stimulus until a compelling sensation of self-motion was reported, which typically occurred after about 15 seconds. To evaluate the time course and total duration of vection, participants were instructed to press one of two keys (depending on direction) whenever they experienced vection, and to keep the key depressed for as long as they experienced vection. A binary signal (sampling rate 1 Hz) was sent to a computer and stored for off-line analysis. Vection onset latency was defined as the time it took for participants to first press the key to indicate the occurrence of vection. Vection magnitude was assessed post exposure by asking participants to rate their experience in terms of the following question: "Whilst watching the moving images, did you get the feeling of motion? That is, did you experience a compelling sensation of self-motion as though you were actually moving?" The endpoints of the 7-point Likert scale were anchored as "not at all" (1) and "very much so" (7) (after Prothero, 1998).

Statistical analysis

The data were analysed twice. The first analysis considered the effects of session order, and because none were identified (Appendix 27), the analyses were repeated assuming no session order effect existed. Since the motion sickness data were of a non-parametric distribution, Wilcoxon matched-pairs signed ranks tests were used. The times to sickness ratings two and three were

heavily negatively skewed because a large number of participants reached the 20 minutes maximum exposure without reporting any symptoms. To minimise the number of ties[1], a similar approach was adopted to that previously performed by Golding et al. (2003) and Golding and Kerguelen (1992). Although a considerable number of participants reached the endpoint without reporting any symptoms according to the sickness rating scale, different SSQ total scores were observed between the conditions in some participants indicating certain conditions to be more provocative than others. Total SSQ scores for such participants were then used to provide weightings in terms of decimal fractions of a time of one second to break ties at 20 min. If total SSQ scores at 20 min were the same for conditions, no change was made to break the tied observations. The same procedure was used to analyse the accumulated sickness rating results. To test for differences between conditions in vection duration and latencies, Tukey's HSD tests were performed. Differences in vection magnitude were analysed using Wilcoxon Signed Ranks tests. Spearman's rho was employed to test for correlations between motion sickness and vection measures.

EXPERIMENT 2

The method in the second experiment was identical to that of the first, apart from the following differences. There were twelve participants (six female and six male) with a mean (± SD) age of 29.1 (± 4.4) years. The mean percentile score for the participants in this study was 59%. Each of the participants was instructed to view a stationary image which consisted of a single frame of the random dot pattern (see figure 2.2) for twenty minutes. Differences between the data of the four experimental conditions in the first experiment and the baseline data were evaluated using Mann-Whitney tests.

[1] The rationale for adopting this approach is based on the fact that ties are disregarded in the Wilcoxon test subsequently resulting in data loss and statistical power (Howell, 2006). Since the weighting is based on the SSQ, which is assumed to measure the same underlying construct (i.e. motion sickness), breaking ties can therefore be considered to increase the sensitivity of the particular measure.

3.4 Results

Individual data obtained in experiment 1 regarding the time-course of motion sickness rating and vection are shown in appendices 4-7. Data obtained in Experiment 2 (baseline) are presented in conjunction with the results of Experiment 1 and are referred to as condition S (stationary).

Sickness ratings

Table 3.1 shows the number of participants reaching each sickness rating in each of the five conditions. Contrary to varying velocity motion in condition FB, none of the participants reported mild nausea during constant velocity motion in conditions F and B. As expected, oscillating roll motion (condition R) induced a substantial amount of side effects with two participants requesting to terminate the session before the 20 minutes time cut-off due to symptom severity.

TABLE 3.1 NUMBER OF PARTICIPANTS REACHING EACH SICKNESS RATING BEFORE THE 20-MIN TIME CUT-OFF.

	Condition				
Sickness rating	S	F	B	FB	R
2	2/12	2/12	3/12	4/12	8/12
3	0/12	0/12	0/12	2/12	3/12
4	0/12	0/12	0/12	0/12	2/12

The time-course of mean sickness ratings is shown for each of the conditions in figure 3.1a. In comparison with conditions F and B, oscillatory motion in condition FB resulted in slightly higher sickness ratings. Mean sickness ratings during constant velocity motion (conditions F and B) did not appreciably differ from the baseline data in experiment 2 (condition S). Highest sickness ratings were observed for condition R. Although data beyond 20 min were not collected, two participants reported feeling 'groggy' and slightly nauseous for more than 4 hours after being exposed to condition R.

The accumulated sickness ratings showed a similar trend and are shown in figure 3.1b. The accumulated sickness rating in condition FB was slightly higher than in conditions F and B although the difference failed to reach statistical significance. The highest accumulated malaise rating was found in condition R and this was significantly higher than the accumulated malaise ratings in all of the other conditions (in each case $p < 0.04$). None of the other differences were found to be significant.

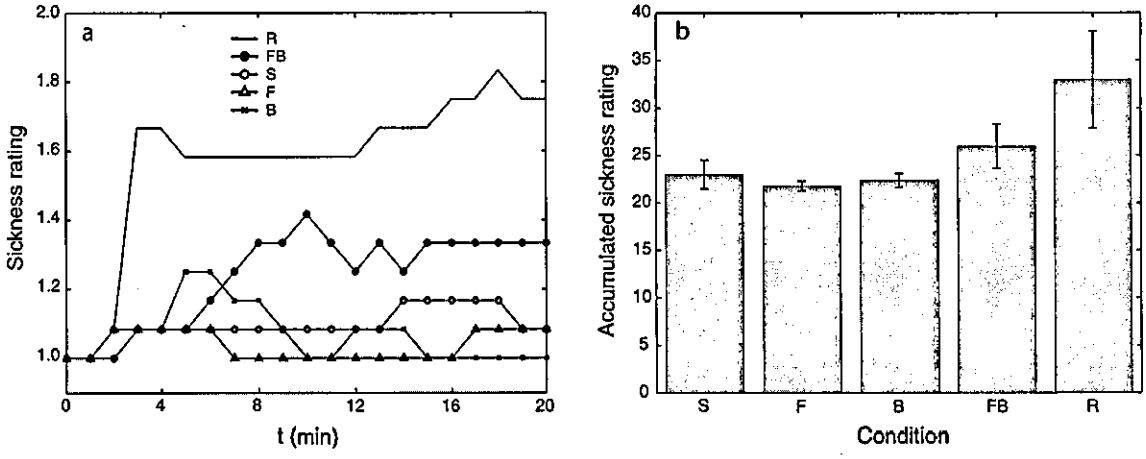


Fig. 3.1 (a) Mean sickness rating as a function of exposure duration. (b) Mean accumulated sickness ratings (± SEM).

Figures 3.2 (a) and (b) show the mean times to achieve sickness ratings 2 and 3, respectively. Symptom onset time tended to be slightly shorter in condition FB in comparison with the two constant velocity conditions F and B. With regard to time to sickness rating 2, backward motion (condition B), in turn, was found to induce symptoms slightly sooner than forward motion (condition F).

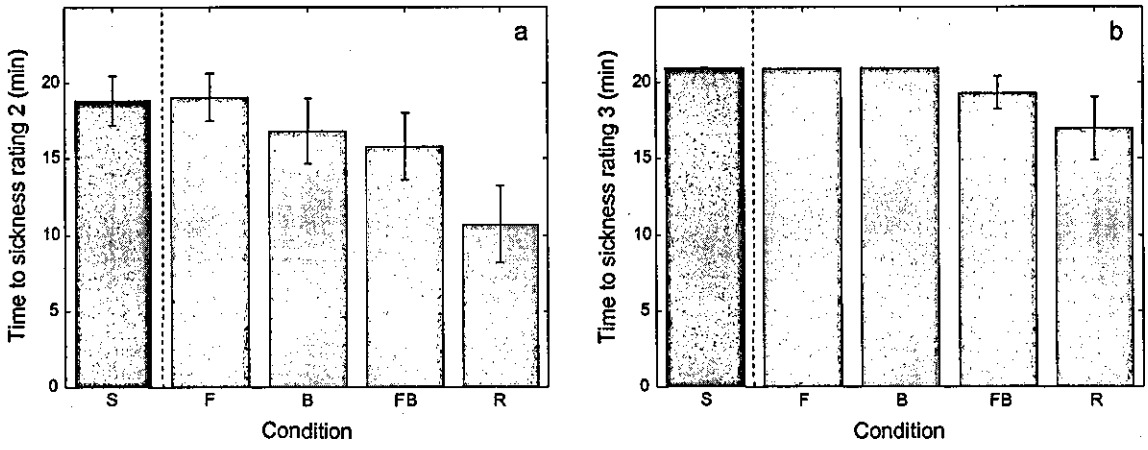


Fig. 3.2 Mean (± SEM) time to reach sickness rating 2 (a) and 3 (b).

Since both time to sickness rating 2 and 3 failed to pass the tests for normality, non-parametric statistics were used. Post-hoc analysis showed that time to sickness rating 2 was significantly shorter in condition R than in the other conditions (in each case $p < 0.04$). Time to sickness rating 3 in condition R was significantly shorter than in condition B. The difference between condition R and conditions F and FB both approached significance ($p = 0.065$ and $p = 0.089$, respectively). None of the other differences were found to be significant.

Figures 3.3 a-d show the SSQ total scores and the SSQ N, O, D subscores for each condition. A similar trend was observed in that varying velocity motion (FB) tended to be slightly more nauseogenic than constant velocity motion (F and B). Contrary to the accumulated sickness ratings, backward motion resulted in slightly lower levels of motion sickness as assessed by the SSQ. These differences however failed to reach the required significance level and significant differences were found between condition R and each of the other conditions only (in each case $p < 0.05$).

The SSQ subscores showed a similar trend with condition FB leading to marginally higher subscores in comparison with conditions F and B. Motion sickness levels during constant velocity motion were again comparable to those observed in experiment 2 (condition S).

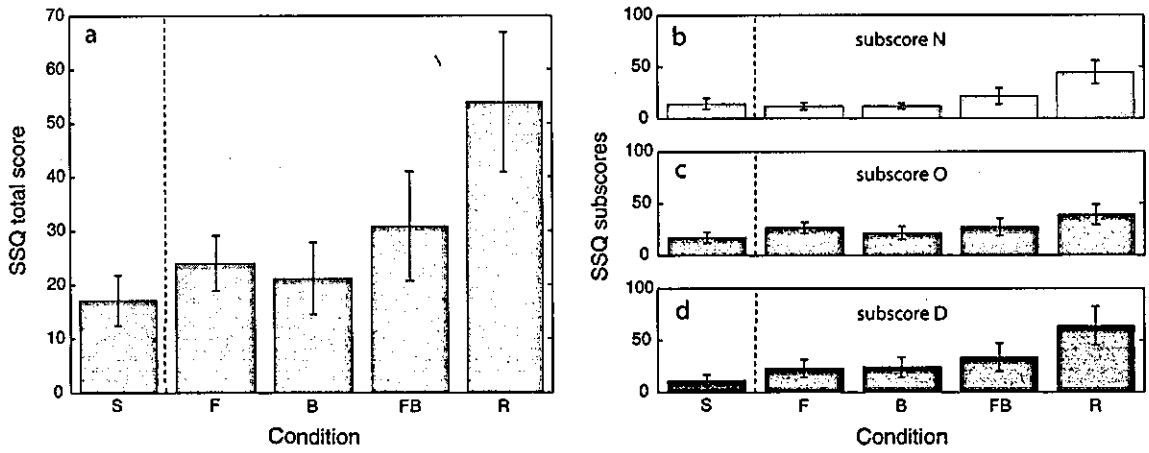


Fig. 3.3 Mean (± SEM) SSQ total scores (a) and SSQ N, O, D subscores (b, c, d, respectively) for each condition.

Post-hoc analysis showed that the SSQ subscore N in condition R was significantly higher than in conditions S, F, B, and FB ($p < 0.03$). The SSQ subscore O in condition R was significantly higher than in conditions B ($p < 0.03$). The SSQ subscore D in turn was significantly higher in condition R in comparison with the other conditions ($p < 0.04$).

The mean changes (post - pre score) in symptom severity of the individual SSQ symptoms, are displayed in Figure 3.4. Despite the absence of optokinetic stimulation in condition S, a small increase in most of the symptoms was nevertheless reported. Unlike the other conditions, none of the participants however reported nausea[2], dizziness, or vertigo, suggesting that movement of the image was associated with these symptoms. Across conditions, a similar pattern was seen as for the other motion sickness indices whereby the largest change in symptoms occurred in condition R, followed by condition FB. Note in particular the larger change in sweating, nausea, vertigo, and stomach awareness.

[2] Note that nevertheless a slight increase in the SSQ subscore N in condition S was observed. Although subscore N is commonly referred to as Nausea subscore (Kennedy et al., 1993), the present results illustrate that the labelling of the composite scores that make up the SSQ subscores need to be interpreted with care.

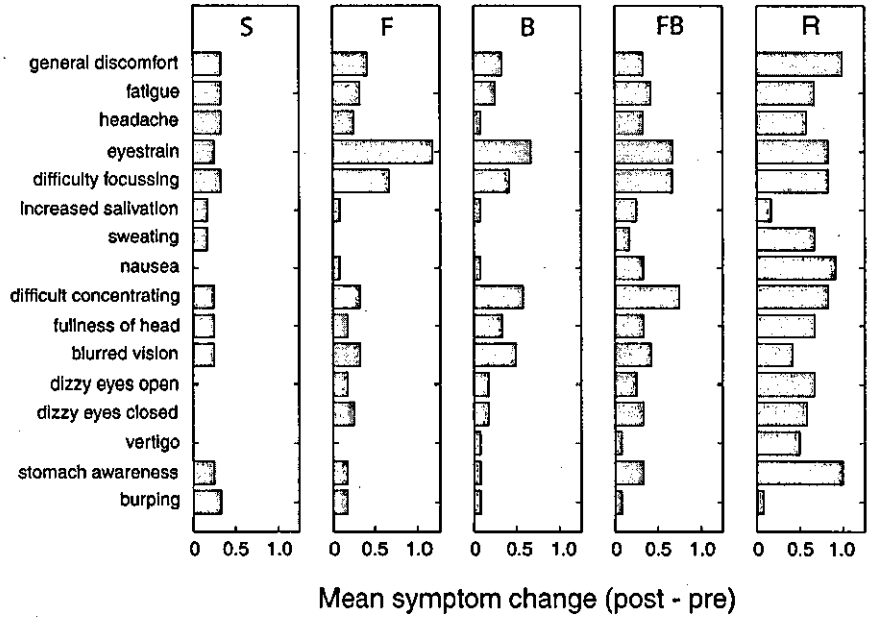


Fig. 3.4 Mean change (post – pre score) in symptom severity of individual SSQ symptoms for the five conditions.

Vection

Following stimulus onset, all participants reported vection during each of the four conditions in experiment 1 (see appendices 4-7 for individual data). The mean vection magnitude ratings are displayed in figure 3.5a. Vection magnitude rating in condition R was found to be significantly higher in comparison with each of the other conditions (in each case $p < 0.02$).

Figure 3.5b shows the mean vection onset times. Vection was most quickly induced during fore-and-aft oscillation in condition FB, whereas longest onset latencies were observed during forward motion at constant velocity in condition F. Tukey's HSD tests revealed none of the differences to reach statistical significance however.

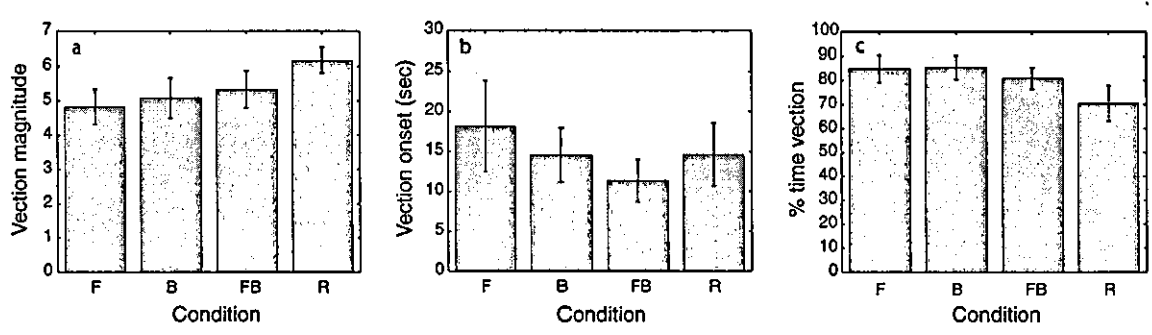


Fig. 3.5 Mean (± SEM) vection magnitude rating (a) vection onset time in seconds (b) and percentage of time vection was experienced (c).

The percentage of the total exposure duration that vection was experienced is shown in figure 3.6c. During constant velocity motion (conditions F and B) vection was experienced for approximately 85% of the time. The total duration was reduced during oscillating motion (conditions FB and R), although these differences were not statistically significant.

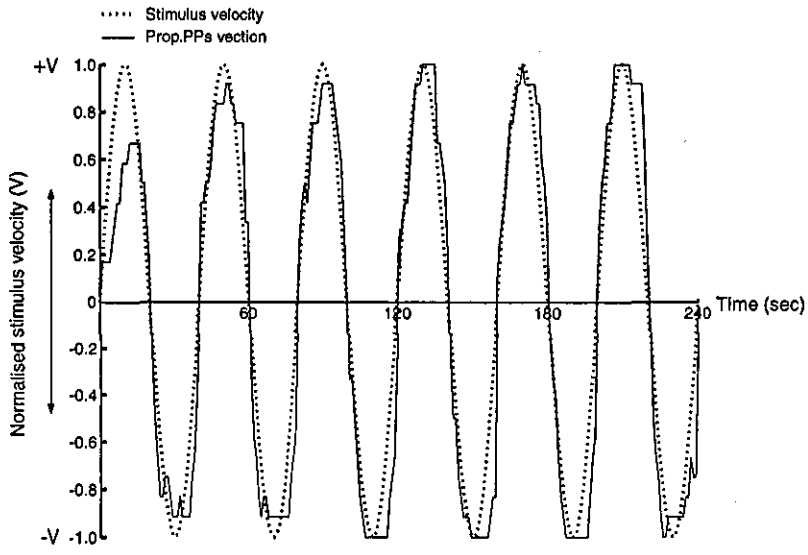


Fig. 3.6 Solid line: proportion of participants (PPs) reporting forward vection (pos. values) and backward vection (neg. values) in condition FB displayed during the first 4 minutes. Dotted line: normalised visual stimulus velocity (V) in condition FB (+V: expanding optic flow; -V: contracting optic flow).

The reduction in the total vection time for oscillating motion can be easily understood by inspection of the proportion of participants reporting vection over time. In figure 3.6 the proportion of participants reporting forward (positive values) and backward (negative values) vection are plotted for the first four minutes in condition FB. In the same graph, stimulus velocity of the sinusoidally oscillating expanding (+V) and contracting (-V) optic flow pattern is also plotted. It can be seen that the proportion of participants reporting vection shows a phase lag with respect to the stimulus velocity. The graph shows that proportion of participants reporting vection increased with stimulus velocity and reached its maximum at peak velocity. Towards the end of each excursion image velocity

was zero (V_0) and consequently no vection was experienced. The effect of inter-individual differences in vection onset times is reflected in the gradual increase in the proportion of participants reporting vection over time reaching 100% in the third stimulus cycle.

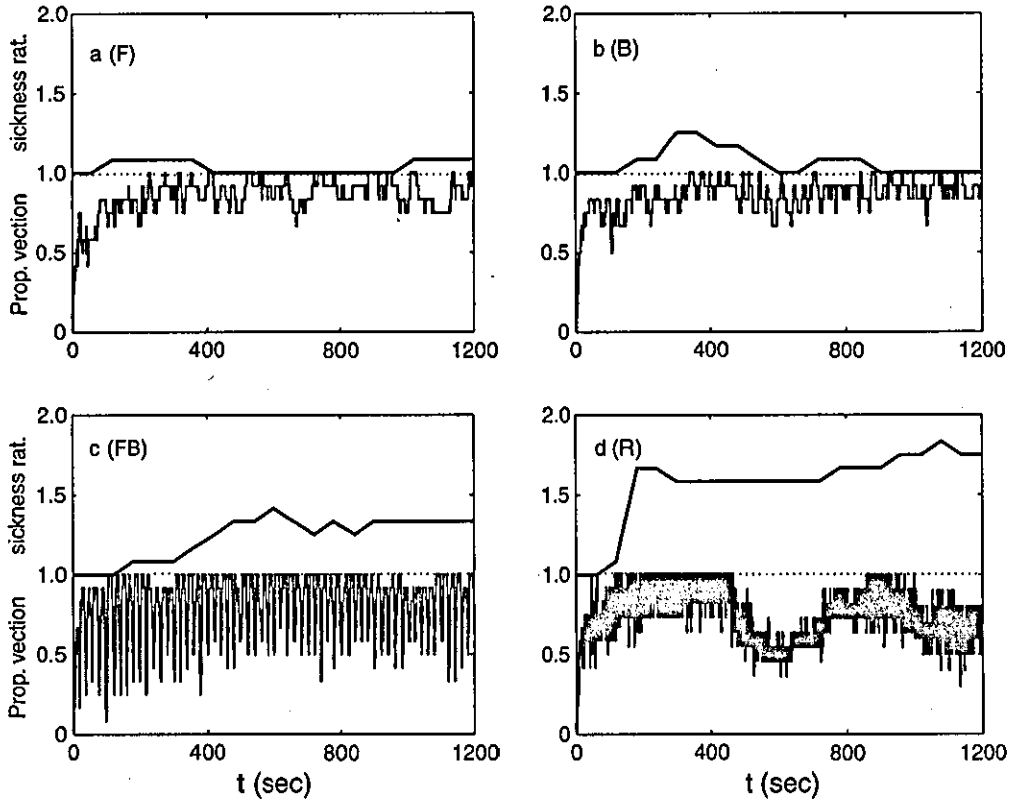


Fig. 3.7 Mean sickness ratings (black line) and proportion of participants reporting vection (grey line) over time for each condition (a-d).

Mean sickness ratings and the proportion of participants reporting vection for each condition over time are shown in figure 3.7a-d. Contrary to conditions F, B, and FB, participants habituated to the visual stimulus in condition R as evidenced by the decrease in the number of participants reporting vection after approximately 7 minutes. However, the proportion of participants reporting vection increased again after about 800 seconds, preceding a further increase in motion sickness. Inspection of the individual data shows that an increase in sickness rating was consistently preceded by the occurrence of vection.

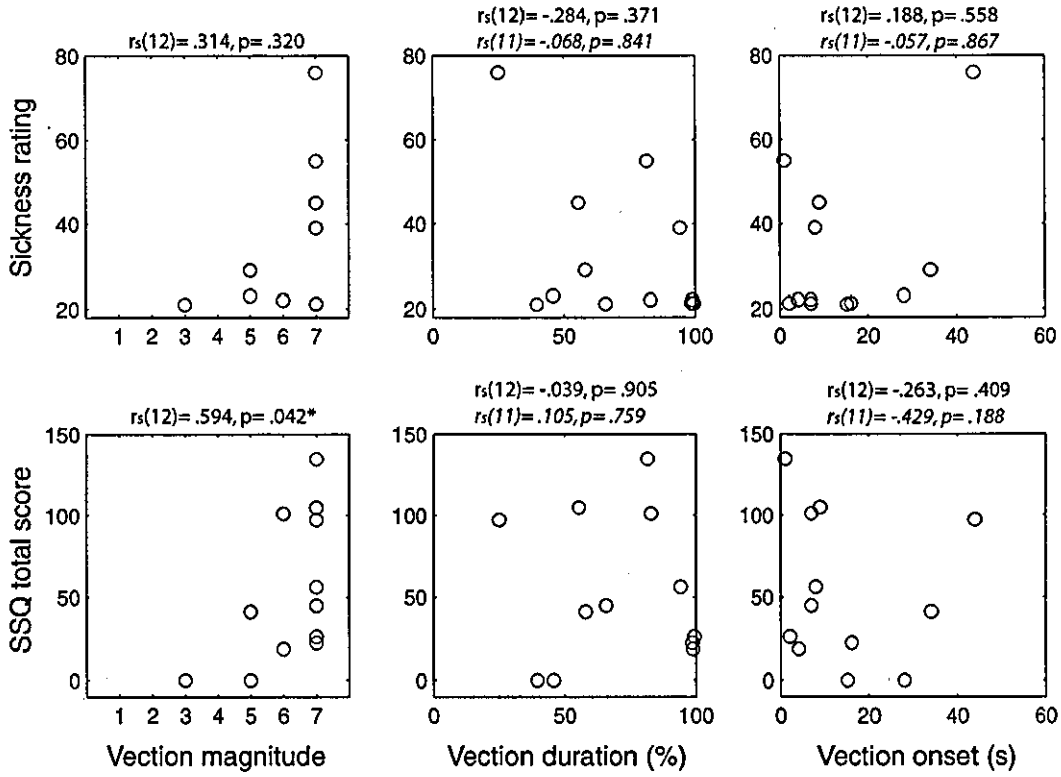


Fig. 3.8 Accumulated sickness rating (top row) and SSQ total score (bottom row) plotted vs. vection magnitude, duration (%), and onset (s) in condition R. Corresponding Spearman's rank correlation coefficients and p-values are shown above each graph. Correlation coefficients and p-values with one of the participants (extreme score) excluded from the analysis are shown in italics.

Considering the low base rate of sickness in conditions F, B, and FB, correlational analysis of motion sickness and vection measures was not meaningful and was therefore restricted to the data in condition R, the condition with the highest motion sickness incidence. In figure 3.8 the accumulated sickness ratings (top row) and SSQ total scores (bottom row) are plotted versus each of the vection measures (from left to right: vection magnitude, duration, and onset time). Spearman's Rank correlation coefficients and corresponding p-values are shown above each graph.

Individuals reporting stronger feelings of vection also reported higher levels of motion sickness and this trend was reflected in both the accumulated sickness ratings and SSQ total scores. The scatterplot of vection duration and motion

sickness showed a slight trend whereby increased vection duration tended to be associated with higher levels of motion sickness, although three out of twelve participants reported vection for almost the entire exposure duration without a considerable increase in symptoms. Susceptible participants also tended to report vection earlier than less susceptible participants. Note that the correlation coefficients regarding the time course of vection (i.e., vection duration and onset) were heavily affected by one participant in particular (see "italics" figure 3.8) who reported vection for only a short period of time after a relatively long onset latency before requesting to terminate the experiment soon after.

3.5 Discussion

Consistent with expectations based on the neural mismatch theory, the level of motion sickness induced by constant velocity visual scene motion in experiment 1 did not rise above the baseline level observed in the absence of any visual motion in experiment 2. Although a step change in visual field velocity as in conditions F and B initially causes an immediate visual-vestibular mismatch, with prolonged stimulation this mismatch is resolved as any constant linear velocity is consistent with the otolith signal at rest. All measures of motion sickness in conditions F and B, including accumulated sickness rating, times to sickness rating 2 and 3, and SSQ total severity score, were essentially equivalent to the baseline data obtained in experiment 2. If the stimuli in these conditions would have been provocative, an exposure duration of 20 minutes should have been more than sufficient time to generate motion sickness. We therefore conclude that horizontal linear motion at constant velocity induces little or no motion sickness. This is consistent with observational reports in fixed-base car simulators using constant velocity driving scenarios such as driving on a motorway (J.A. Horne, personal communication, July, 2004), which contrasts highly with other vehicle simulation conditions (Kennedy et al., 1990).

The current results also showed that, at least for constant velocity motion, backward motion did not appreciably lead to higher levels of motion sickness than forward motion as previously suggested (Kolasinski, 1995; McCauley & Sharkey, 1992). Whereas the accumulated sickness ratings and time to

sickness rating 2 indicated backward motion to be slightly more provocative, the SSQ scores failed to show an effect of motion direction. In fact, a recent study by Bubka et al. (2007) indicated backward motion to be actually less nauseogenic than forward motion induced by expanding optic flow patterns. In explaining their results, the authors suggested that experience with expanding optic flow patterns and the sensory inputs that usually accompany them have resulted in a central nervous system expectancy about what the appropriate inputs should be during forward self-motion. Less experience with backward self-motion may result in a lower level of expectation regarding what the appropriate sensory inputs should be for contracting flow patterns. This lower level of neural expectancy may subsequently lead to less sensory conflict and consequently less motion sickness generated by contracting flow patterns. This also fits in with the finding that in the current study backward motion was consistently more effective in inducing vection than forward motion as previously also reported by Berthoz et al. (1975). Consistent with the visual-vestibular conflict hypothesis regarding vection (Zacharias & Young, 1981), the smaller degree of conflict with contracting flow patterns may impose less inhibition leading to shorter vection onset times.

Despite the absence of visual scene motion in condition S, a slight increase in symptoms was nevertheless found. It seems likely that these symptoms were caused by the prolonged viewing of the large projection screen at a distance of 90 cm with the head fixed in a chin/headrest. The subjective reports of discomfort may have been further exacerbated by reactivity effects as participants are alerted to symptoms by being asked about motion sickness symptoms.

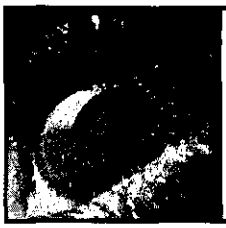
The main finding of this study was that oscillating fore-and-aft motion (condition FB) led to little or no motion sickness despite continuous visual-vestibular conflict. Although the motion sickness incidence was slightly higher in condition FB compared to conditions F, B, and S, these differences were not found to be statistically significant. There are a number of possible explanations to account for this finding. The simplest and most obvious possibility is that the sample used in this study was not susceptible to visually induced motion sickness. This

explanation can be ruled out, however, as a considerable proportion of the participants did report symptoms in condition R. Alternatively, the inability to find statistically significant differences may be due to small sample sizes. Finally, the low incidence in condition FB may be accounted for by the particular frequency used in this study. This raises the question of whether visually induced motion sickness is frequency-dependent, as is inertial motion sickness. Since the vestibular system becomes less responsive in the lower frequency range (Benson, 1990; Guedry, 1974), the degree of conflict in the current study can be argued to be relatively low and may thus increase at higher frequencies. Recently, it has been hypothesised that visually induced motion sickness is most readily evoked at a frequency around 0.06 Hz, which has been related to perceptual uncertainty at this frequency (Duh et al., 2004). This issue will be elaborated on in the following chapter.

The present study confirms the powerful effects of visual scene motion in inducing illusory sensations of self-motion. All participants reported a compelling sensation of vection in all four visual scene motion conditions during a substantial period of the total exposure duration. The finding that sustained vection did not invariably led to motion sickness demonstrates that vection per se does not induce motion sickness. On the other hand, inspection of the individual time course data in condition R showed that increases in motion sickness symptoms were consistently preceded by the occurrence of vection, in line with the idea that vection is a prerequisite for visually induced motion sickness to occur (Hettinger et al., 1990). Individual differences in susceptibility to such sensory conflicts may explain why some participants remained symptom free despite experiencing vection of varying velocity. The correlational analysis for condition R further suggested that individuals who reported stronger feelings of vection also reported more motion sickness. These findings suggest that current efforts to enhance spatial presence within synthetic environments by means of maximising the effectiveness of self-motion simulation (e.g., Riecke et al., 2005) inadvertently run the risk of increasing motion sickness incidence within such environments.

3.6 Conclusions

Optic flow patterns simulating both constant and varying velocity horizontal motion induces compelling illusions of self-motion. Contrary to expectations on the basis of the neural mismatch theory, sustained conflict during varying velocity stimulation led to little or no motion sickness. This raises the question whether this may have been due to the low-frequency oscillation employed and thus whether visually induced motion sickness is frequency dependent.



C_4
Frequency dependence of VIMS

4.1 Summary

This chapter describes two experiments in which the frequency response of VIMS was explored for oscillating linear motion in the fore-and-aft axis. Whereas motion sickness in physically moving environments is known to peak at around 0.2 Hz, it has recently been suggested that VIMS peaks at around 0.06 Hz, the crossover frequency where the summed response of the visual and vestibular self-motion systems is maximized. Within the frequency range investigated in this study (0.025 – 1.6 Hz), VIMS peaked within the frequency range of 0.2 to 0.4 Hz. It was concluded that the crossover frequency hypothesis cannot be extrapolated to linear motion in the fore-and-aft axis.

4.2 Introduction

In the previous chapter, the effect of constant versus varying velocity optokinetic stimulation on VIMS was examined. The rationale for this study was based on the fact that the vestibular system provides information about changing velocities only, whereas the visual input contributes supplementary information about constant velocity (Howard, 1986). Following a sensory cue-conflict approach, motion sickness was therefore expected to occur during varying but not constant velocity motion (Oman, 1991; Reason & Brand, 1975).

Contrary to this prediction, however, varying velocity stimulation did not significantly increase the level of motion sickness in comparison with either constant velocity stimulation or the complete absence of optokinetic stimulation (i.e., baseline condition). The question subsequently raised was whether this may have been due to the frequency chosen for the particular motion profile used, i.e., fore-and-aft oscillation at a frequency of 0.025Hz. Hence, the main impetus of this chapter is to evaluate the hypothesis that the level of VIMS is dependent upon the frequency of motion.

It is known that the important physical characteristics of nauseogenic motion include the frequency, and less reliably, the acceleration and amplitude of the motion (Griffin, 1990; Guignard & McCauley, 1990). In laboratory studies using linear and angular oscillation, motion sickness peaks at a frequency of approximately 0.2 Hz, whereas motion at other frequencies produces little or no sickness (Bos & Bles, 1998; Donohew & Griffin, 2004; Golding & Markey, 1996; Golding et al., 2001; Griffin, 1990; Guignard & McCauley, 1990).

It has been suggested that the predominant frequency of oscillation of the visual display also plays an important role in the generation of VIMS (Kennedy et al., 1996), and that, similar to true motion sickness, imposed visual motion at a frequency around 0.2 Hz is most provocative (Hettinger et al., 1990). Besides the known provocative frequency range with regard to inertially induced motion sickness, this latter hypothesis was based on the observation that visual stimuli below 0.5 Hz led to higher vection magnitudes (Post et al., 1989), that vection magnitude induced by dynamic rod and frame stimuli (i.e., visual roll motion) was found to be highest at 0.213Hz within the frequency range of 0.013 Hz to 0.213

Hz[1] (Babler & Ebenholtz, 1989), as well as the finding that the vestibular ocular reflex approaches unity gain and zero phase lag at around 0.2 to 0.25 Hz and higher (Paige, 1989). However, there appears to be no published data to substantiate this specific frequency dependence for VIMS. Furthermore, Hettinger et al. (1990) failed to elaborate on the question of why oscillating motion at a frequency around 0.2 Hz would be most nauseogenic.

As discussed in chapter 1, Parker and co-workers (Duh et al., 2004; Lin et al., 2005; Parker et al., 2001) recently hypothesised VIMS to peak around the frequency where the summed response of the visual and vestibular self-motion systems is maximal. By plotting the vestibular and visual self-motion response curve, this so-called "crossover frequency" was determined to be around 0.06 Hz (see figure 1.6b) (Duh et al., 2004). Since both systems would provide strong signals at this frequency, it was argued that conflicting visual and vestibular self-motion cues at this frequency would be most provocative. Subsequent studies indeed seemed to provide support for their hypothesis (Duh et al., 2004; Lin et al. 2005).

Considering the close correspondence of the visual and vestibular self-motion system response characteristics for both angular and linear motion (Benson, 1990; Berthoz et al., 1979), the crossover hypothesis may also explain the low incidence of motion sickness during oscillating fore-and-aft motion observed in the previous study considering that the employed frequency (0.025 Hz) was below the crossover frequency.

The studies by Duh et al. (2004) and Lin et al. (2005) have provided corroborating evidence for the crossover hypothesis with regard to angular motion (i.e., yaw and roll, respectively). However, thus far there are no controlled data relating frequency to the sickness inducing potency of fore-and-aft motion. Hence, the aim of this study was i) to explore the frequency dependence of VIMS for linear motion in the fore-and-aft axis, and ii) to evaluate the crossover hypothesis for this type of linear motion.

An experiment was conducted in which stationary observers were exposed to random dot radial optic flow patterns simulating oscillating linear motion in the

[1] Note that this may represent a ceiling effect considering the restricted frequency range investigated.

fore-and-aft axis at four different frequencies: 0.025, 0.05, 0.1, and 0.2 Hz. Based on the crossover hypothesis, it was predicted that linear oscillation at a frequency of 0.05 Hz would result in elevated levels of motion sickness compared with oscillations at both higher and lower frequencies.

EXPERIMENT 1

4.3 Methods

Participants

Twelve healthy participants (seven male and five females) with a mean (± SD) age of 29.8 (± 5.8) years gave their informed consent to participate in the study, following its approval by the Loughborough University Ethical Advisory Committee. All participants had intact vestibular function, were not receiving any medication, and had normal or corrected-to-normal vision. The mean MSSQ percentile score for the participants in this study was 44%, indicating the sample to be slightly less susceptible to motion sickness than the normal population (Golding, 1998).

Apparatus and stimuli

The stimuli were generated in real time with a frame rate of 60 Hz using Matlab (version 6.5) running on a DELL GX computer fitted with a Matrox Millenium P750 graphics card (64Mb). The images were backprojected onto a tangent screen (190 cm x 145 cm) with a Hitachi CP-X958W/E projector (1024 x 768 pixels). The display consisted of 500 white dots with a luminance of 10.82 cd/m2 randomly positioned on a black background of 0.35 cd/m2 (Michelson contrast ratio of 0.94). Dot velocity and size varied exponentially as a function of their simulated location in depth (Andersen & Braunstein, 1985). Dot size at the eye ranged from 0.22° at the middle to 2.97° at the periphery. For technical reasons, there were no dots at the very centre of the visual scene, and as a consequence, there was a black disc subtending 8.75° of visual angle (see figure 2.2).

All participants were exposed to random dot optic flow patterns simulating oscillating linear motion in the fore-and-aft axis at four different frequencies, 0.025, 0.05, 0.1, and 0.2 Hz. To allow for a direct comparison with the findings from Duh et al. (2004) in the context of the crossover hypothesis, peak optical velocity was also held constant in this study (34°/sec), and thus, displacement and acceleration covaried with frequency (see appendix 28 for further details on the visual stimuli). To suppress optokinetic reflexes (Busettini et al., 1997; Lappe et al., 1998; Niemann et al., 1999), participants were instructed to fixate a red dot (0.57° of visual angle) projected at eye height in the centre of the screen. Participants each viewed the moving displays binocularly from a fixed viewpoint with their head held in position by a head/chinrest at a distance of 90 cm from the screen. To occlude the edges of the screen and other peripheral features, participants wore goggles, which limited the visual field to 65° (h) x 59° (v) of angle. Acoustic localisation cues were masked by pink noise (75 dB) transmitted to earphones worn by the participant. In addition, auditory alerting bleeps (500, 750, and 1000 Hz at 100 dB) were played at random intervals throughout the exposure duration. Communication with the participants during exposure was via a microphone.

Design

Each participant completed the four conditions on a Latin square design. To limit any bias caused by habituation to the stimulus and to avoid possible circadian rhythm effects, session were spaced at least 24 hrs apart and took place at the same time of day. Exposure duration was 20 minutes for each session.

Motion sickness measures

Before and after each session, the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) was completed by each participant. The measure of interest was the change in the SSQ total scores (post – pre exposure score).

In addition, participants rated the severity of their motion sickness every minute on Bagshaw and Stott's (1985) motion sickness scale (1, no symptoms; 2, mild symptoms, but no nausea; 3, mild nausea; 4, moderate nausea). The experiment

was stopped at sickness rating 4 ('moderate nausea') or after 20 min, whichever was the sooner. Participants who reached a sickness rating of 4 and stopped before 20 min were assigned continuation values of 4. The measures of interest were the time for participants to first report a sickness rating of 2 ('time to sickness rating 2') and 3 ('time to sickness rating 3'), the maximum sickness rating, and the sum of the sickness ratings over the 20 min exposure duration ('accumulated sickness rating'). If no symptoms were reported, an accumulated sickness rating and symptom onset score of 21 was recorded.

Vection measures

Vection was defined as a compelling feeling of self-motion, such as "the feeling you get when a train moves next to you and you mistake it for your own motion." To ensure participants differentiated between object- and self-motion, prior to the first session, they were exposed to oscillating roll motion (0.125 Hz; peak-to-peak amplitude of 120°) until a compelling sensation of self-motion was reported. This typically occurred after about 15 seconds.

To evaluate the time course and total duration of vection, participants were instructed to press a key whenever they experienced vection, and to keep the key depressed for as long as they experienced vection. Vection onset latency was defined as the time it took for participants to first press the key to indicate the occurrence of vection.

Vection magnitude was assessed post exposure by asking participants to rate their experience in terms of the following question: "Whilst watching the moving images, did you get the feeling of motion? Did you experience a compelling sensation of self-motion as though you were actually moving?" The endpoints of the 7-point Likert scale were anchored as "not at all" (1) and "very much so" (7). In addition, participants were asked to separately evaluate vection magnitude for the forward and backward direction. In the first question participants were asked to give an overall vection magnitude rating. In two following questions, participants were asked to evaluate vection magnitudes for each of the two motion directions individually, i.e., forward and backward motion.

Data analysis

The data were analysed twice. The first analysis considered the effects of session order, and because none were identified (Appendix 27), the analyses were repeated assuming no session order effect existed. Since the motion sickness data were of a non-parametric distribution, Wilcoxon Signed Ranks tests were used. The symptom onset time and accumulated sickness rating distributions were heavily negatively skewed due to the large number of participants reached the 20 min maximum exposure without reporting any symptoms. To minimise the number of ties, a similar approach was adopted to that previously performed by Golding et al (2003). This used the fact that different SSQ total severity scores were observed between the four conditions in some participants, indicating certain conditions to be more provocative to them than others. SSQ total severity scores for such participants were then employed to break ties. If SSQ total severity scores at 20 min were the same for different conditions, the results were accepted as tied.

Because of the abnormal distribution of the data (i.e., positive skew), differences between conditions were tested for significance using non-parametric Wilcoxon Signed Ranks tests. To test for differences between conditions in vection duration, latencies, and magnitude, Tukey's HSD tests were performed. Correlations between motion sickness and vection measures were analysed using Spearman's rho.

4.4 Results

Individual data obtained in experiment 1 regarding the time-course of motion sickness rating and vection are shown in appendices 8-11.

Sickness rating per-exposure

Table 4.1 shows the number of participants reaching each sickness rating stage before the 20-min cut-off. It appears that an increase in frequency was associated with greater motion sickness. None of the participants reported nausea (sickness rating 3) during 0.025 and 0.05 Hz oscillation. During 0.2 Hz

oscillation, two participants requested to terminate the experiment before the maximum 20 min time cut off (at minute 17 and 18).

TABLE 4.1 NUMBER OF PARTICIPANTS REACHING EACH SICKNESS RATING STAGE BEFORE THE 20 MIN CUT-OFF

	Condition			
Sickness rating	0.025 Hz	0.05 Hz	0.1 Hz	0.2 Hz
2 Mild symptoms, but no nausea	5/12	5/12	7/12	8/12
3 Mild nausea	0/12	0/12	2/12	3/12
4 Moderate nausea	0/12	0/12	0/12	2/12

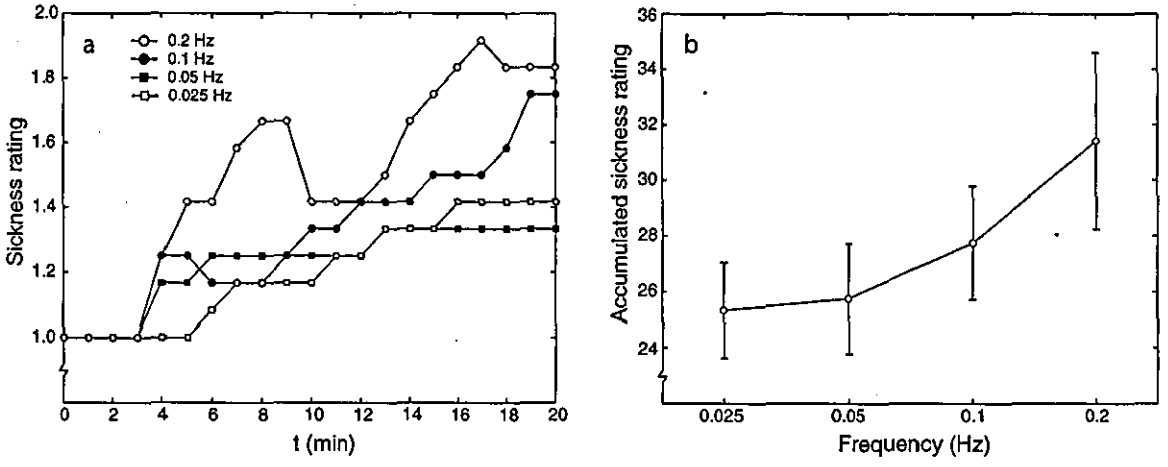


Fig. 4.1 (a) Mean sickness rating as a function of time for each of the four conditions. (b) Mean accumulated sickness rating (± SEM) as a function of frequency.

The time-course of mean sickness ratings and the mean accumulated sickness ratings for each of the four conditions are shown in figure 4.1. With increasing frequency, there was a tendency for participants to report greater mean sickness ratings over time. The accumulated sickness rating during 0.2Hz oscillation was higher than during 0.05 Hz oscillation ($p = 0.012$) and 0.025 Hz oscillation ($p = 0.025$). The accumulated sickness rating during 0.1 Hz oscillation was significantly higher compared with 0.025 Hz oscillation ($p = 0.017$). The other differences seen were not statistically significant.

Symptom onset times

Figure 4.2 shows the mean times to achieve sickness ratings 2 (mild symptoms, but no nausea) and 3 (mild nausea). Since both measures failed to pass the tests for normality, non-parametric statistics were used. Both times to achieve sickness ratings two and three became shorter with increasing frequencies. Post-hoc analysis showed that time to sickness rating 2 during 0.2 Hz oscillation was significantly shorter than during 0.05 Hz oscillation ($p = 0.014$) and 0.025 Hz oscillation ($p = 0.008$). Time to sickness rating 2 was significantly shorter during 0.1 Hz oscillation compared with oscillation at 0.025 Hz ($p = 0.008$). Time to sickness rating 3 during 0.1 Hz oscillation was significantly shorter than during 0.025 Hz oscillation ($p = 0.034$). No other differences were found to be significant.

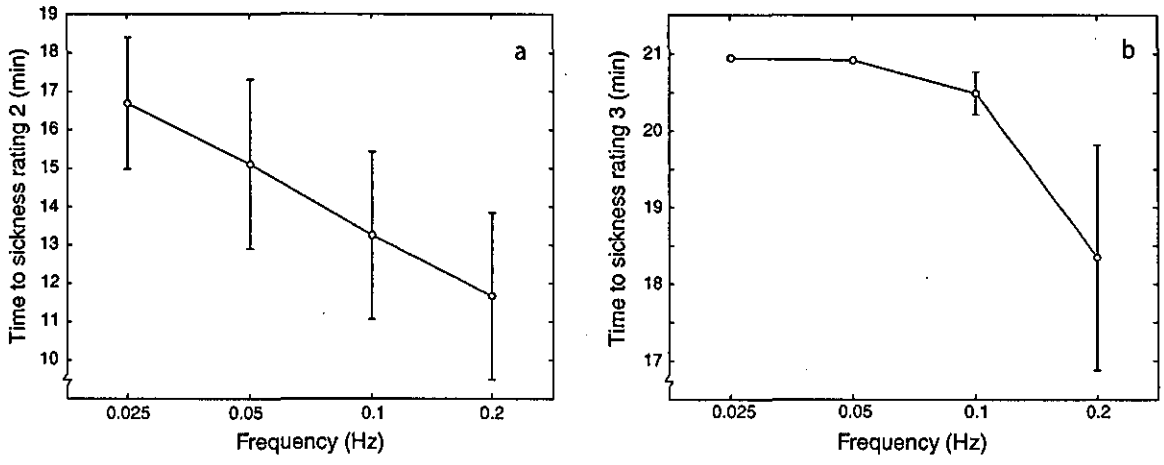


Fig. 4.2 Mean (± SEM) time to sickness rating 2 (a) and 3 (b) as a function of frequency.

Simulator Sickness Questionnaire (SSQ)

Figure 4.3 shows the SSQ total scores and the SSQ N, O, D subscores for each condition. SSQ total scores and subscores increased with increasing frequency. Post-hoc analysis showed that the SSQ total sore and N subscore were significantly higher during 0.1 Hz than during 0.025 Hz oscillation ($p = 0.030$; $p = 0.007$, respectively). No other differences were found to be significant.

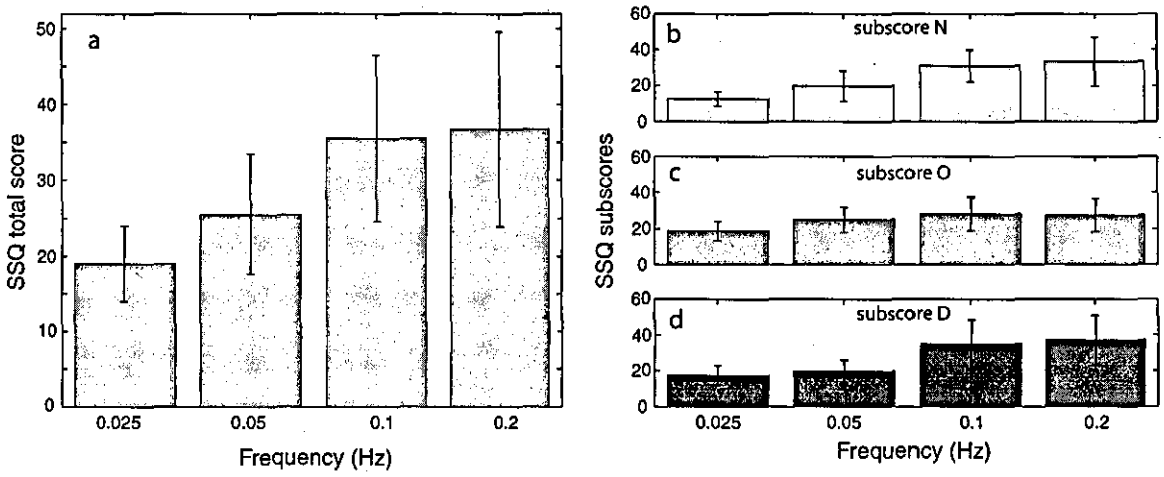


Fig. 4.3 Mean (± SEM) SSQ total scores (a) and SSQ N, O, D subscores (b, c, d, respectively) for each condition.

The mean changes (post - pre score) in symptom severity of the individual SSQ symptoms, are displayed in Figure 4.4. With the exception of "fatigue", symptom severity tended to increase with frequency. The largest change in symptom severity was observed for "eyestrain".

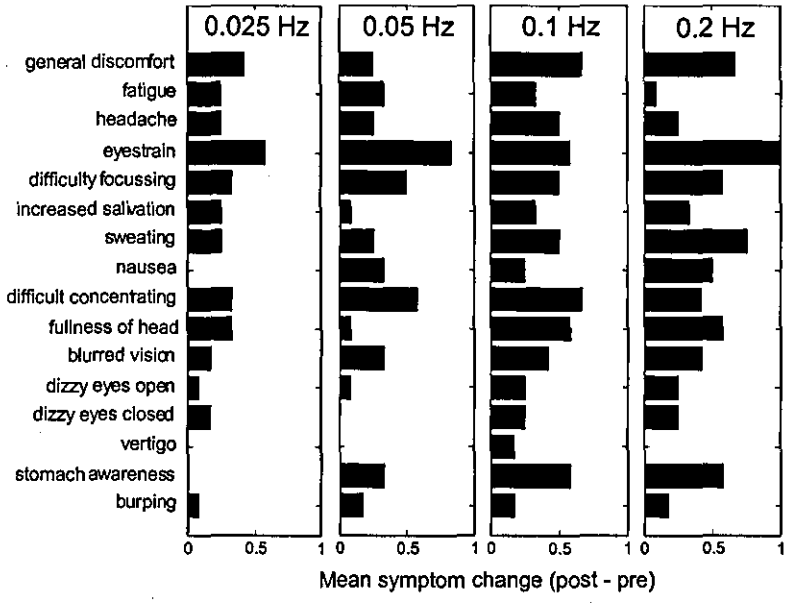


Fig. 4.4 Mean change (post – pre score) in symptom severity of individual SSQ symptoms for the four conditions.

Vection magnitude, onset, and duration

Eleven of 12 participants experienced vection in the direction opposite that of the display motion in all four conditions. One participant did not experience any

vection during 0.025 Hz oscillation but did so during oscillation at the other frequencies.

An unexpected finding was that, despite the absence of angular components in the optic flow pattern, a number of participants reported that they were not moving fore and aft along the line of sight but were being swung on a giant swing and perceived their chin rocking on the chinrest, akin to the somatogravic illusion during inertial linear acceleration (Clark & Graybiel, 1949). Since this visual equivalent of the somatogravic illusion (see General discussion) was recurrently reported during the initial sessions of the study, all participants were subsequently asked to describe their motion path post-exposure. In 16 out of 48 sessions (12 participants x 4 frequencies) this illusion was reported. Acknowledging the limitations of these data, it is noteworthy that individuals who reported this illusory tilt (n = 6) also tended to be more susceptible to motion sickness and vection (see appendix 12).

Figure 4.5a shows the mean overall vection magnitude ratings (O) as well as the forward (F) and backward direction vection magnitude ratings (B) per condition. Post-hoc analysis showed that backward vection magnitude was significantly higher for 0.1 Hz than for 0.2 Hz oscillation ($p = 0.026$). None of the other differences reached the level of significance required however.

Consistent with earlier findings by Berthoz et al. (1975), it can be seen in figure 4.5a that backward vection magnitude was consistently rated higher than forward vection. This difference reached statistical significance for 0.025 Hz oscillation ($p = 0.007$), 0.05 Hz oscillation ($p = 0.007$), and 0.1 Hz oscillation ($p = 0.004$), but not for 0.2 Hz oscillation ($p = 0.077$).

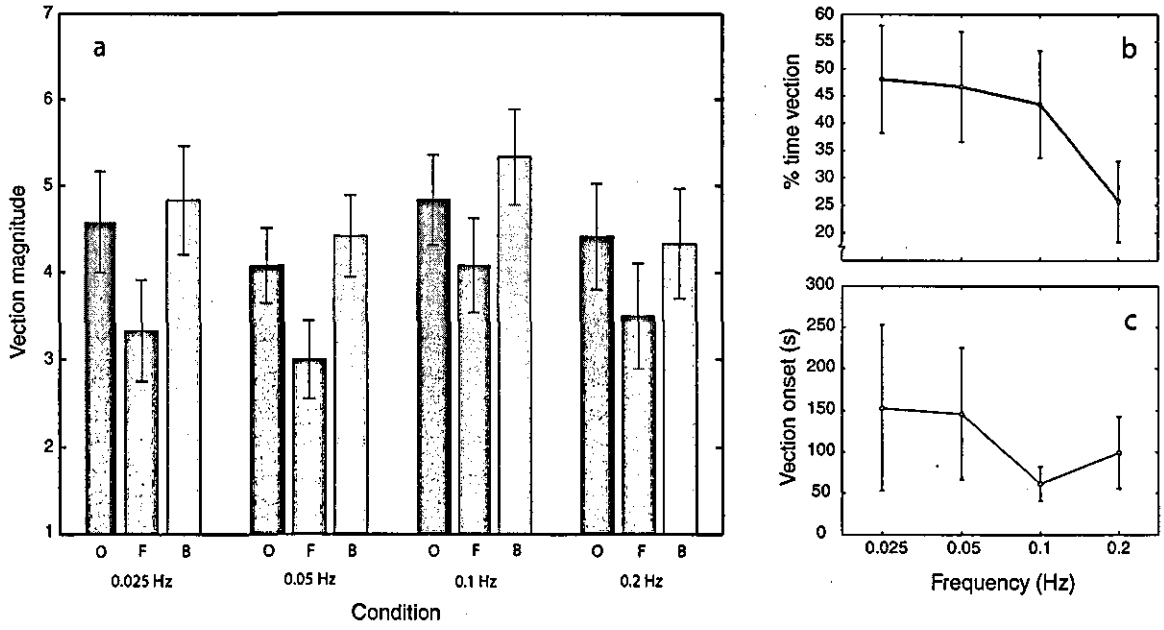


Fig. 4.5 (a) Mean (± SEM) vection magnitude overall rating (O); Forward vection magnitude (F); Backward vection magnitude (B); (b) Mean (± SEM) percentage of time vection was experienced; (c) Mean (± SEM) vection onset time in seconds.

In figure 4.5, the percentage of the total exposure duration that vection was experienced (b), and the mean vection onset times (c) are plotted as a function of frequency. The percentage of time vection was experienced decreased with increasing frequency ($p < 0.001$). Tukey's HSD tests revealed that the percentage of time vection was experienced during 0.2 Hz oscillation was significantly higher compared with the other frequencies ($p < 0.05$). Vection onset times also tended to decrease with frequency. Because the vection onset times failed to pass the tests for normality, non-parametric statistics were used. Post-hoc pairwise comparisons showed none of the differences to be significant (Wilcoxon Signed Ranks test).

Vection time course

Mean sickness ratings and the proportion of participants reporting vection over time are shown in figure 4.6a-d for each condition. Whereas the mean sickness rating showed a gradual increase over time, a slight decrease in the proportion of participants reporting vection over time was observed, which was particularly

evident during 0.2 Hz oscillation. Note also the concomitant drop in mean sickness rating after about 540 seconds during 0.2 Hz oscillation (4.6d).

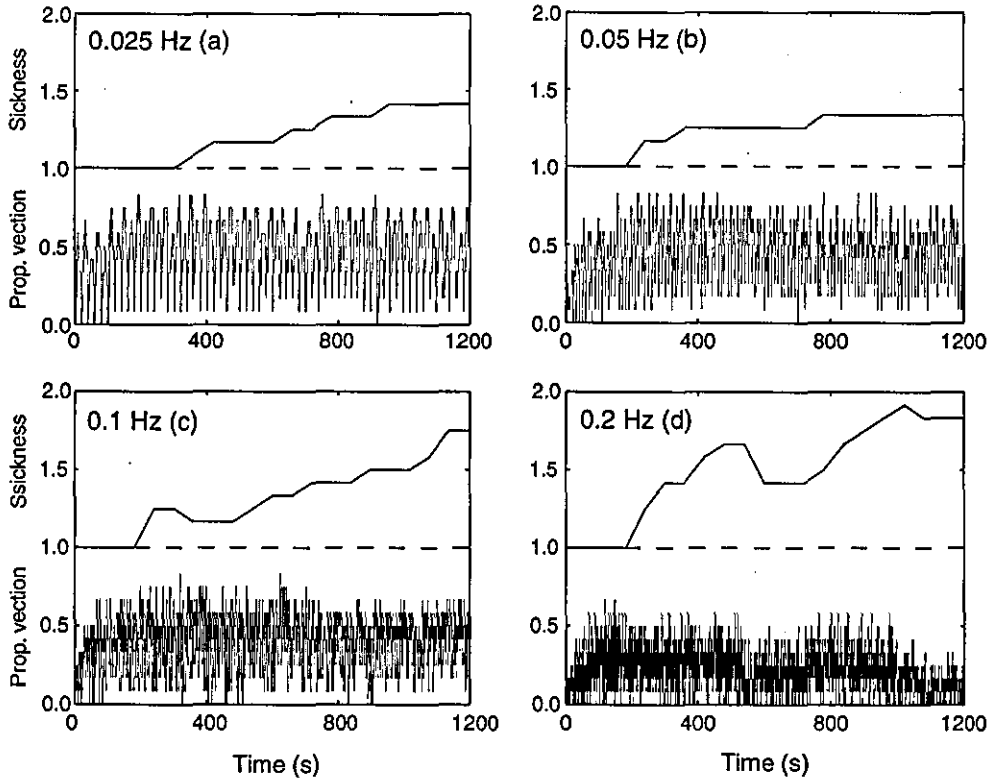


Fig. 4.6 (a-d) Mean sickness ratings and proportion of participants reporting vection over time for each condition.

Vection - motion sickness

Table 4.2 shows the Spearman rank correlations between the accumulated sickness ratings and vection magnitude ratings, percentage of time vection was experienced, and vection onset times, for each condition separately and pooled over the four conditions. Individuals who reported higher levels of motion sickness tended to report stronger feelings of vection, for a longer period of time, and sooner than less susceptible individuals.

TABLE 4.2 SPEARMAN CORELATION COEFFICIENTS FOR ACCUMULATED SICKNESS RATING AND VECTION MAGNITUDE, DURATION, AND ONSET, FOR EACH CONDITION AND AVERAGED OVER THE FOUR CONDITIONS (POOLED)

Condition	Vection magnitude	Vection duration	Vection onset
0.025 Hz	r_s = .281 p = .377	r_s = .569 p = .053	r_s = -.250 p = .434
0.05 Hz	r_s = .672* p = .017	r_s = .417 p = .177	r_s = -.521 p = .083
0.1 Hz	r_s = .575 p = .050	r_s = .290 p = .361	r_s = -.364 p = .245
0.2 Hz	r_s = .861* p = .000	r_s = .843* p = .001	r_s = -.370 p = .236
Pooled	r_s = .595** p = .000	r_s = .442** p = .002	r_s = -.422** p = .003

4.5 Discussion: Experiment 1

The aim of this study was to explore the frequency dependence of VIMS for linear oscillatory motion in the fore-and-aft axis. According to the crossover hypothesis (Duh et al., 2004), elevated levels of motion sickness are predicted to occur in the mid-frequency range around 0.06 Hz, with lower levels of motion sickness both below and above this frequency. The results of the present study are however not in agreement with this hypothesis. Within the frequency range 0.025 – 0.2 Hz, the level of VIMS consistently increased with increasing frequency and reached a maximum at the highest frequency of 0.2 Hz. This trend was consistent across the different motion sickness measures including accumulated sickness ratings, times to sickness rating 2 and 3, number of participants achieving mild nausea, and total SSQ scores.

The discrepancy between the current findings and the findings by Duh et al. (2004) and Lin et al. (2005) could arguably be explained by differences in stimulus presentation. Whereas in the study by Duh et al. the visual stimulus was presented via a head-mounted display with a field-of-view (FOV) of 48° x 36°, the large-screen projection system employed in the current study allowed for a slightly larger FOV of 65° x 59°. Lin et al. (2005) proposed that the crossover frequency could be altered as a function of FOV. Based on the fact that the relative gain of the visual self-motion system increases with increasing FOV (e.g., Lestienne et al., 1977), the crossover frequency should consequently be higher with a larger FOV than with a smaller FOV. However, subsequent results

obtained using a driving simulator with a variable FOV (60° vs. 180° horizontal) revealed no interaction effect of FOV on the frequency dependence of motion sickness (Lin et al., 2005). We therefore speculate that the crossover hypothesis cannot be extrapolated to linear motion, and that the frequency dependence of VIMS for linear motion differs from that for angular motion.

EXPERIMENT 2

Referring back to figure 1.6b, it can be seen that the vestibular system reaches unity gain at a frequency of 0.2 Hz and higher. The visual system's response, on the other hand, becomes less responsive at these higher frequencies and fails to respond at a frequency of 0.8 Hz. Following the rationale put forward by Duh et al. (2004) motion sickness would consequently be expected to decrease at frequencies above 0.2 Hz. At the same time, vection would not be expected to be experienced at frequencies above 0.8 Hz. To test these hypotheses and explore the frequency dependence of linear motion, a second experiment was conducted in which the frequency range was extended to 1.6 Hz.

4.6 Methods

The method used was identical to that of experiment 1, apart from the following differences. There were twelve participants (5 female and 7 male) with a mean (± SD) age of 24.6 (± 2.8) years, of which one participant also participated in experiment 1. The mean MSSQ percentile score for the participants in this study was 44%.

The frequencies used in experiment 2 were: 0.2, 0.4, 0.8, and 1.6 Hz at a constant average peak optical velocity of 34°/sec. Due to the higher frequency range employed, it was anticipated that the time taken to switch between keys depending on vection direction could result in an underestimation of the total time vection was experienced. Therefore, participants were instructed to press a

single key to indicate either forward or backward vection, and to keep it depressed for as long as vection was experienced.

4.7 Results

Sickness rating per-exposure

Table 4.3 shows the number of participants reaching each sickness rating before the 20-min time cut-off. The lower frequencies were associated with greater motion sickness and moderate nausea was reported during 0.2 and 0.4 Hz oscillation only. Two participants had to terminate the experiment during 0.2 Hz oscillation after 6 and 8 min; one of these participants also requested to stop the experiment during 0.4 Hz oscillation after 6 min. (See appendices 13-16 for individual data).

TABLE 4.3 NUMBER OF PARTICIPANTS REACHING EACH SICKNESS RATING STAGE BEFORE THE 20 MIN CUT-OFF

	Condition			
Sickness rating	0.2 Hz	0.4 Hz	0.8 Hz	1.6 Hz
2 Mild symptoms, but no nausea	10/12	9/12	8/12	6/12
3 Mild nausea	2/12	4/12	2/12	1/12
4 Moderate nausea	2/12	1/12	0/12	0/12

The time-course of mean sickness ratings and accumulated sickness ratings for each of the four conditions are shown in figure 4.7. With increasing frequency, there was a tendency for participants to report lower sickness ratings. Post-hoc comparisons revealed that the accumulated sickness rating during 0.2 Hz oscillation was significantly higher than during 1.6 Hz oscillation ($p = 0.031$).

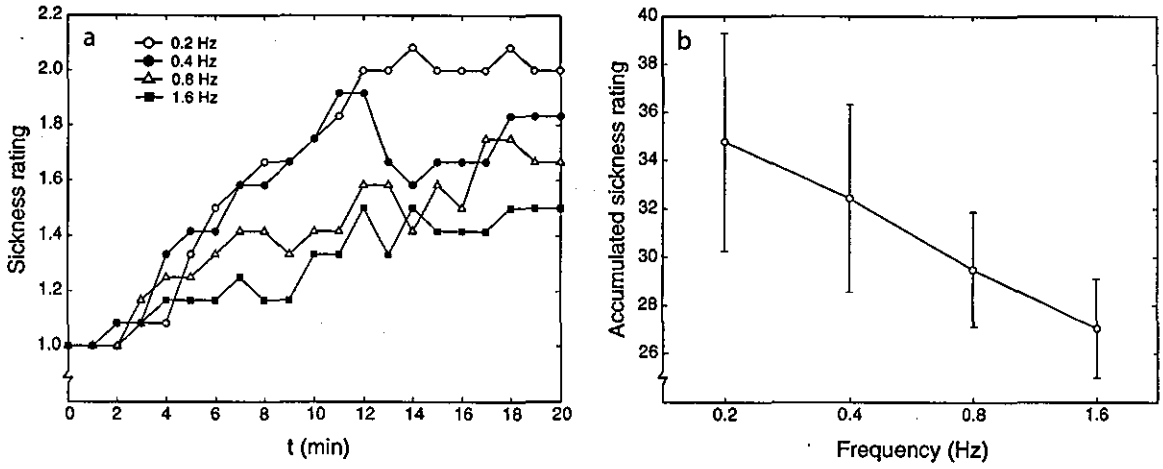


Fig. 4.7 (a) Mean sickness rating as a function of time for each of the four conditions. (b) Mean accumulated sickness rating (± SEM) as a function of frequency.

Symptom onset times

The mean times to achieve sickness ratings 2 (mild symptoms, but no nausea) and 3 (mild nausea) are displayed in figure 4.8. Time to achieve sickness rating 2 was shortest during 0.2 Hz oscillation and became longer with increasing frequencies. Time to achieve sickness rating 3 was shortest during 0.4 Hz oscillation and became longer with frequencies both below and above 0.4 Hz. Due to the abnormal distribution of both time to sickness rating 2 and 3, non-parametric tests were employed. Post-hoc comparison showed that time to sickness rating 2 during 1.6 Hz oscillation was significantly longer than during 0.4 Hz oscillation ($p = 0.031$). No other differences were found to be significant.

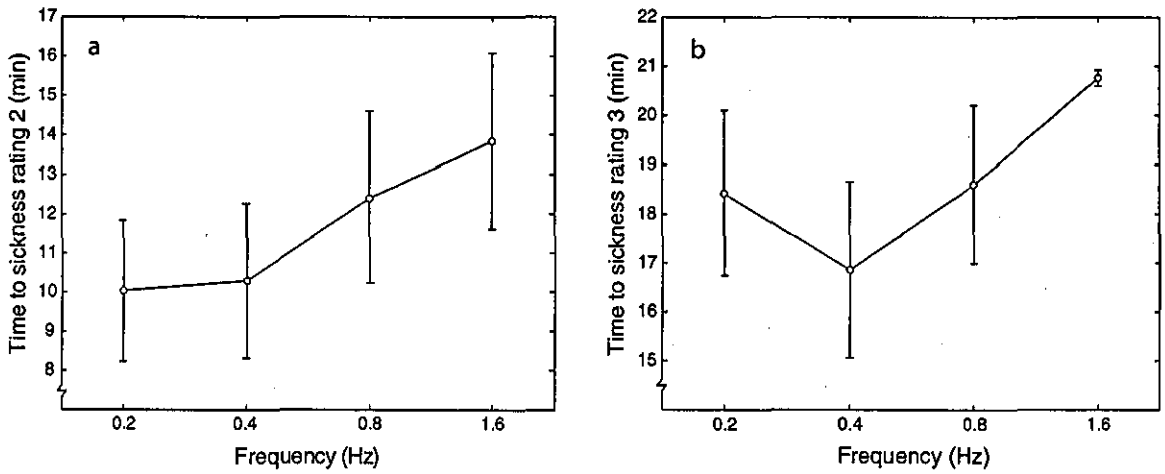


Fig. 4.8 Mean (± SEM) time to achieve sickness rating 2 (a) and 3 (b) for each condition.

Simulator Sickness Questionnaire (SSQ)

The SSQ Total Scores and the SSQ N, O, D subscores are displayed in Figure 4.9 for each condition. Except for the N subscore, which showed a steady decrease with increasing frequency, no clear trend was observed. Post-hoc comparisons revealed none of the differences to be significant.

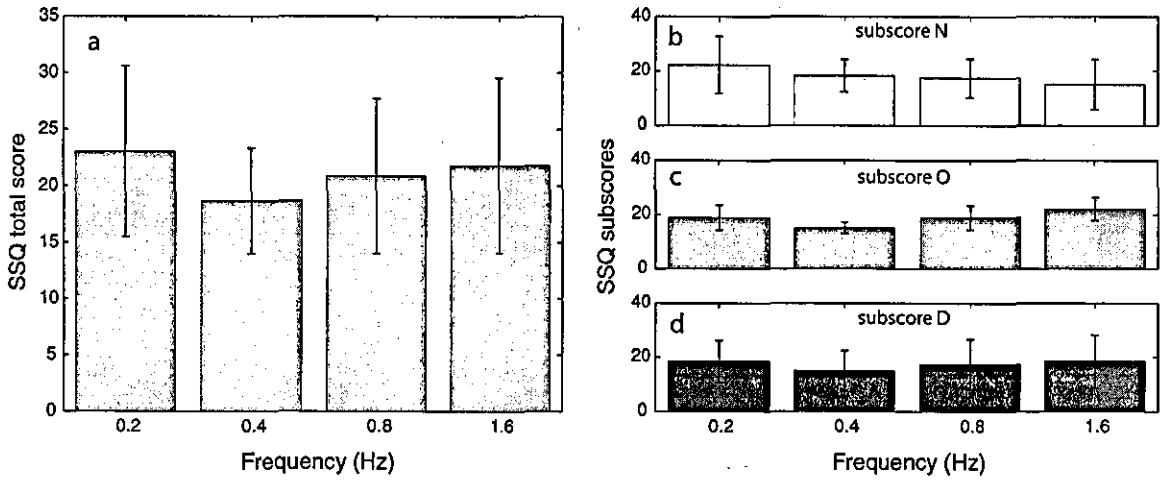


Fig. 4.9 Mean (± SEM) SSQ total scores (a) and SSQ N, O, D subscores (b-d, respectively) for each condition.

Closer inspection of the data revealed that the SSQ total scores were heavily affected by one participant (Pp 5) in particular whose scores were classified as outliers and extreme scores (see figure 4.10a). With this participant excluded from the analysis, the SSQ total scores slightly decreased with increasing frequency (figure 4.10b), although post-hoc comparisons revealed none of the differences to be significant.

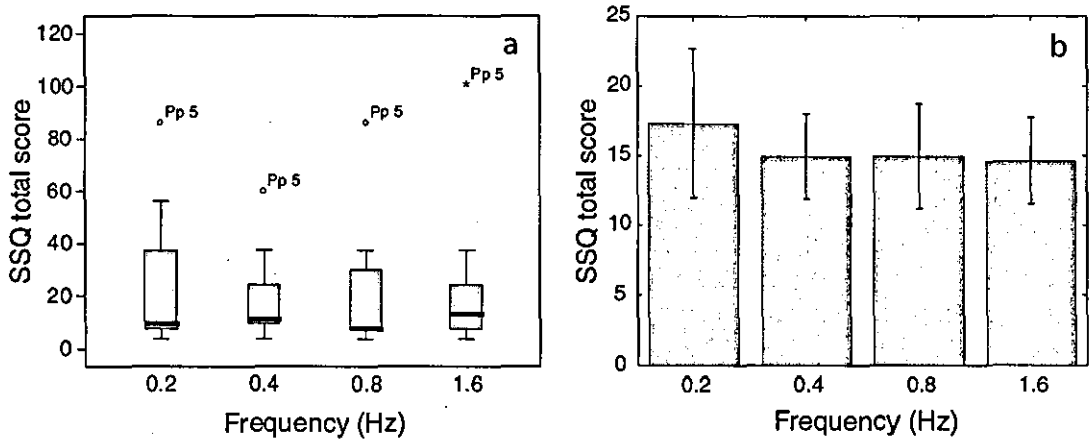


Fig. 4.10 (a) Boxplot of the SSQ total scores (outliers are indicated by circles, extreme scores are indicated by asterisks). (b) Mean (± SEM) SSQ total scores for each condition excluding outlier (participant 5).

Figure 4.11 shows the mean changes (post - pre score) in symptom severity of the individual SSQ symptoms. Except for the change in "eyestrain", which tended to increase with increasing frequency, no clear trend was observed for any of the remaining symptoms. The largest mean change occurred for "eyestrain".

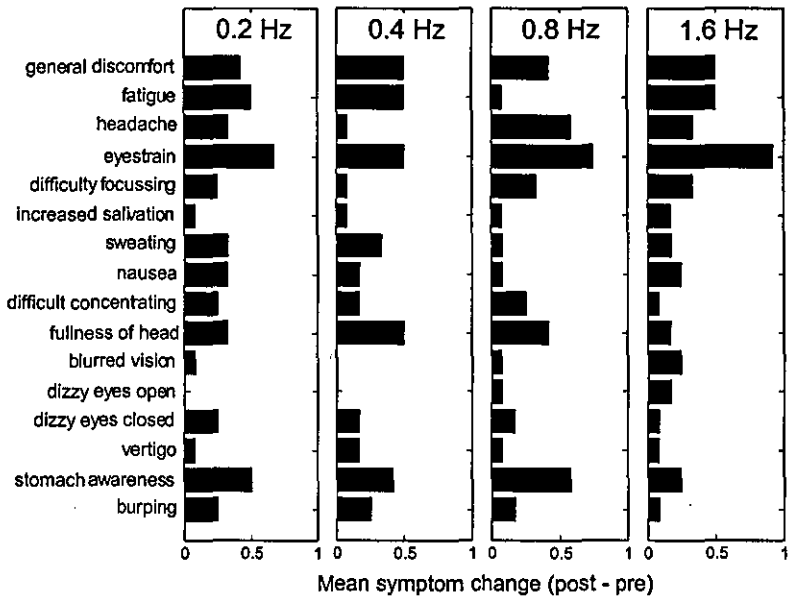


Fig. 4.11 Mean change (post – pre score) in symptom severity of individual SSQ symptoms for the four conditions.

Vection magnitude, onset, and duration

During 0.8 Hz oscillation, three participants did not report any vection, and one participant did not report vection during 1.6 Hz oscillation. Figure 4.12a shows the mean overall (O) vection magnitude ratings, subsequently separated into forward (F) and backward direction vection magnitude ratings (B), per condition. Mean vection magnitude rating during 1.6 Hz oscillation was significantly lower than during 0.8 Hz ($p = 0.014$), 0.4 Hz ($p = 0.011$), and 0.2 Hz oscillation ($p = 0.005$). The mean vection magnitude rating during 0.8 Hz was significantly lower than during 0.2 Hz oscillation ($p = 0.020$).

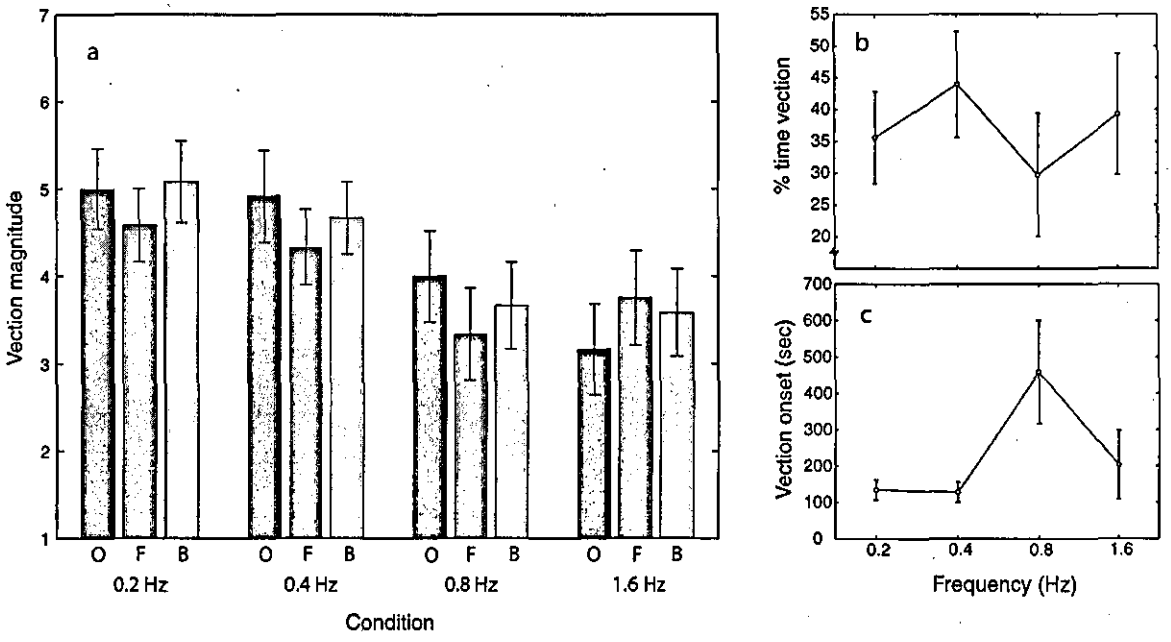


Fig. 4.12 (a) Mean (± SEM) vection magnitude overall rating (O); Forward vection magnitude (F); Backward vection magnitude (B); (b) Mean (± SEM) percentage of time vection was experienced; (c) Mean (± SEM) vection onset time in seconds.

Post-hoc analysis of the forward and backward vection magnitudes revealed the mean forward vection magnitude rating during 0.8 Hz oscillation to be significantly lower than during 0.4 Hz ($p = 0.013$), and 0.2 Hz oscillation ($p = 0.037$). The mean backward vection magnitude rating during 1.6 Hz oscillation was significantly lower than during 0.4 Hz ($p = 0.022$), and 0.2 Hz oscillation ($p = 0.010$). During 0.8 Hz oscillation, the vection magnitude rating was significantly lower than during 0.2 Hz oscillation ($p = 0.010$).

Consistent with the findings in experiment 1, backward vection magnitude ratings were consistently higher than forward vection magnitude ratings with the exception of condition 1.6 Hz. None of these differences reached the required significance level however.

The visual somatogravic illusion was reported by two participants during 0.2 Hz oscillation only. None of the participants reported this illusion at the higher frequencies.

In figure 4.12 b and c, the percentage of time vection was experienced, and the mean vection onset times are plotted as a function of frequency. Post-hoc Tukey's HSD tests revealed no significant differences in the amount of time vection was experienced between the four conditions.

Vection onset times tended to be longer with increasing frequency. Although at first sight this may appear to be inconsistent with the finding that the total amount of time vection was experienced did not differ across conditions, participants frequently experienced "drop-out" periods during which no vection was reported. Consequently, any effects of differences in vection onset times are obscured by the noise within the total time vection was experienced.

Vection onset times failed to pass the tests for normality and hence, pairwise comparisons were made using Wilcoxon Signed Ranks tests. Vection onset time during 0.8 Hz oscillation was significantly longer than during 0.2 Hz ($p = 0.050$), 0.4 Hz ($p = 0.015$), and 1.6 Hz oscillation ($p = 0.026$). None of the other differences were statistically significant.

Vection time course

Mean sickness ratings and the proportion of participants reporting vection over time are shown in figure 4.13 a-d for each condition. As also observed in the first experiment, the proportion of participants reporting vection tended to decrease after about 7 min (± 420 sec). In addition, individual data (see appendices 13-16) again showed increases in sickness rating to be consistently preceded by the occurrence of vection.

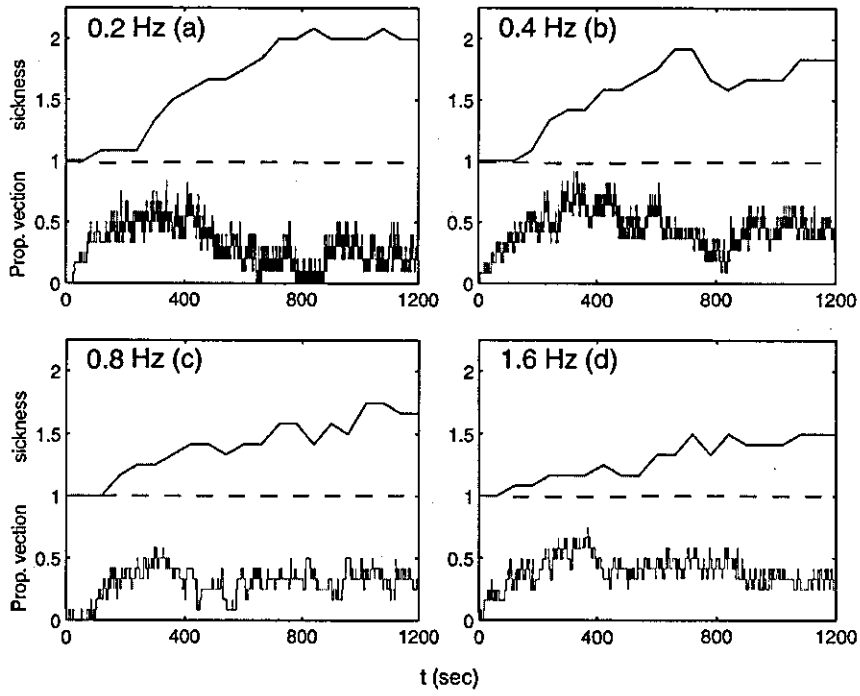


Fig. 4.13 Time course of mean sickness ratings and proportion of participants reporting vection for each condition (a-d).

Vection – motion sickness

Table 4.4 shows the Spearman rank correlations between the accumulated sickness ratings and vection magnitude ratings, percentage of time vection was experienced, and vection onset times, for each condition individually and pooled over the conditions. Individuals who reported higher levels of motion sickness tended to report stronger feelings of vection and for a longer period of time than less susceptible individuals. The relationship between accumulated sickness ratings and vection onset times failed to show a clear trend.

TABLE 4.4 SPEARMAN CORELATION COEFFICIENTS FOR ACCUMULATED SICKNESS RATING AND VECTION MAGNITUDE, DURATION, AND ONSET, FOR EACH CONDITION AND AVERAGED OVER THE FOUR CONDITIONS (POOLED)

Condition	Vection magnitude	Vection duration	Vection onset
0.2 Hz	r_s = .348 p = .267	r_s = .601* p = .039	r_s = .014 p = .966
0.4 Hz	r_s = .490 p = .160	r_s = .466 p = .127	r_s = .183 p = .568
0.8 Hz	r_s = .349 p = .266	r_s = .315 p = .318	r_s = .043 p = .894
1.6 Hz	r_s = .268 p = .400	r_s = .339 p = .282	r_s = -.145 p = .654
Pooled	r_s = .536** p = .000	r_s = .430** p = .002	r_s = -.050 p = .738

4.8 Discussion: Experiment 2

The aim of the second experiment was to further explore the motion sickness frequency response by extending the frequency range from 0.2 to 1.6 Hz. Contrary to the findings in the first study, motion sickness tended to decrease with increasing frequency although this trend was not entirely consistent across the different measures. In particular, time to sickness rating 3 was shorter for 0.4 Hz than for 0.2 Hz, whereas the number of participants reporting mild nausea was highest for 0.4 Hz. Only marginal differences in total SSQ scores were observed over this frequency range. This suggests the SSQ to be a slightly less sensitive measure of motion sickness.

Based on the visual and vestibular system's self-motion response (see figure 1.6b), motion sickness was hypothesised to decrease at frequencies above 0.2 Hz. Whereas the vestibular system reaches unity gain at a frequency of 0.2 Hz and higher, the visual system's response becomes less responsive at these higher frequencies. Consequently, the degree of conflict can thus be expected to decrease with increasing frequency. Apart from the inconsistency observed for time to sickness rating 3, this was indeed seen.

The observed vection data are however incongruent with those reported by Berthoz et al. (1975) and Duh et al. (2004) according to which no vection is experienced at a frequency of 0.8 Hz. The current results showed however that vection was reported at a frequency of 1.6 Hz, the highest frequency investigated. Recently, Palmisano et al. (2003) have shown that, despite continuous visual-vestibular conflict, vection can even be induced by high frequency jittering optic flow patterns in otherwise stationary observers. Palmisano et al. explained this observation referring to Brandt et al.'s (1998) observation that vection activates the medial parieto-occipital visual area, while simultaneously deactivating the parieto-insular vestibular cortex. Brandt et al. concluded that when self-motion perception is dominated by vision (e.g. driving a car at a constant velocity), vestibular information about self-motion is partially suppressed. Further, they claimed that this deactivation of the vestibular system was adaptive, since the vertical vestibular activity provided by car motions and/or secondary involuntary head accelerations often provide inadequate or misleading information about self-motion.

4.9 General discussion

Two studies were conducted to explore the frequency dependence of VIMS for linear oscillatory motion in the fore-and-aft axis. Within the frequency range of 0.025 to 1.6 Hz, the level of motion sickness was maximal within the frequency range of 0.2 - 0.4 Hz. Whereas the SSQ total scores, accumulated sickness rating and time to sickness rating 2 indicated motion sickness to peak at 0.2 Hz, time to sickness rating 3 indicated 0.4 Hz oscillation to be most nauseogenic (see figure 4.14 below). Although it is not possible to identify a single frequency of maximum nauseogenicity on the basis of the current data, the results of this study are not in agreement with the prediction of the crossover hypothesis according to which a maximum effect is expected to occur at a frequency of around 0.06 Hz (Duh et al., 2004).

The crossover frequency was determined on the basis of the frequency response curve of the semicircular canals (Melvill Jones & Milsum, 1965) and not the otoliths. Consequently, it can be argued that with regard to linear motion as detected by the otolith organs, the observed discrepancy may be explained by a shift in the crossover frequency due to a difference in the frequency response of the otoliths. However, this is unlikely to explain the current results since both psychophysical and neurophysiological data show the otolith organs to have a similar frequency response to that of the semicircular canals (Benson, 1990; Howard, 1986). Consequently, a similar crossover frequency is expected.

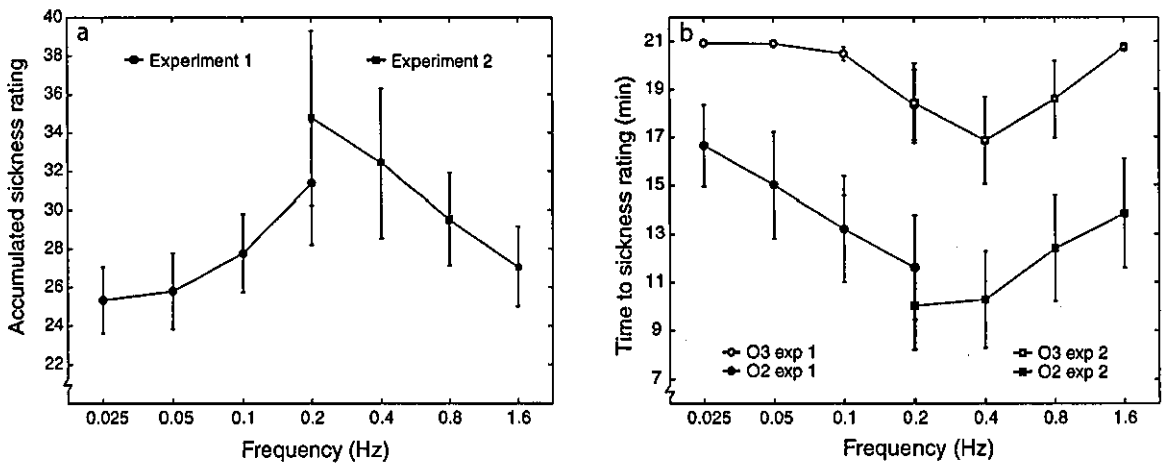


Fig. 4.14 Mean (± SEM) accumulated sickness rating (a) and mean (± SEM) time to sickness rating 2 (O2) and 3 (O3) (b) as a function of frequency for experiment 1 and 2.

Contrary to the findings by Duh et al. (2004) and Berthoz et al. (1975; 1979), the first experiment of the current study also failed to replicate the low-pass filter characteristics of the visual self-motion system. Most notably within the frequency range of 0.025 to 0.2 Hz, vection magnitude ratings were not inversely related to the frequency of imposed oscillation. These discrepancies between data could be accounted for, at least in part, by the differences in procedure. In the study by Berthoz et al. (1975), for example, participants were asked to indicate vection magnitude on-line by pressing a lever, whilst consecutively being exposed to oscillating motion patterns of differing frequencies each lasting for about 2 minutes. In the current study, by contrast, vection magnitude was assessed post exposure only, with considerably longer exposure durations of 20 minutes allowing for adaptation to occur (see figure 4.6 and 4.13), as well as inter-exposure intervals between different motion patterns of at least twenty-four hours. This discontinuous procedure may contain too much noise for an objective demonstration of a frequency effect.

The striking similarity in frequency-dependence between true motion sickness and VIMS observed in the present study lends support for Hettinger et al.'s (1990) proposition that both true and visual oscillating motion at a frequency around 0.2 Hz most readily evokes motion sickness. It is as yet unclear, however, why this would be.

One possible explanation for the frequency effect observed may be related to the fact that the vestibular system becomes increasingly responsive towards the higher frequency range (Benson, 1990; Guedry, 1974). At low frequencies where the vestibular system is less responsive, the discrepancy between the visual self-motion signal and expected vestibular self-motion signal is relatively small. With increasing frequency, however, the vestibular signal that would normally accompany the visual scene motion would concurrently increase in strength and accordingly the subsequent degree of conflict. The observation that the level of motion sickness steadily decreased above around 0.2 Hz may in turn be explained by the declining response of the visual self-motion system to high-frequency visual scene motion as also reflected in the decrease in vection magnitude towards the highest frequencies (see figure 4.12). Maximum sickness

may thus occur at that frequency where i) the gain of the vestibular system reaches unity, and ii) the visual self-motion system is still sufficiently responsive.

Regarding true motion sickness, a number of hypotheses have been put forward to explain the peak at around 0.2 Hz. Benson (1988) proposed that during low frequency oscillation motion sickness occurs due to a phase error in motion signals from the otoliths and somatosensory receptors[2]. Von Gierke and Parker (1994) further elaborated on this by suggesting a potential conflict not only between the otoliths and somatosensory receptors but also the visceral graviceptors. Stott (1986), on the other hand, suggested an intraotolith conflict at low frequency oscillations. The central nervous system expects the otoliths overall output to average 1G over periods of time greater than around 0.5 seconds. Unlike walking or running, which occur at higher frequencies (> 1 Hz), this expectation is violated during sustained low frequency oscillations. As there is no direct involvement of the vestibular system, other than it being silent, neither of these hypotheses is able to explain the frequency response of VIMS.

Recently, the peak in motion sickness at approximately 0.2 Hz observed during inertial horizontal linear acceleration has been linked to the tilt-translation ambiguity of the otolith afferent signal at this frequency (Wood, 2002). During horizontal acceleration in darkness, the central nervous system can interpret a change in direction of the gravitoinertial force vector detected by the otoliths as either head-body tilt with respect to gravity, or translation of the head-body moving in space (Howard, 1986). As a consequence, horizontal acceleration may result in perceptual errors when the gravitoinertial force vector is accepted as the true vertical. A well known example in aviators of this so called somatogravic illusion (SGI) is the sensation of a nose-up change in attitude during sustained acceleration in the line of flight, and, conversely, the apparent nose-down attitude during deceleration (e.g., Graybiel et al., 1979). This tilt-translation ambiguity manifests itself also in vestibulo-ocular reflexes during lateral horizontal linear acceleration whereby torsional rather than horizontal otolith-ocular responses have been reported (Lichtenberg et al., 1982; Paige &

[2] This hypothesis was originally suggested by Mach as early as 1875.

Seidman, 1999; Wood, 2002), suggesting an output from the vestibular system similar to that during tilt.

This tilt-translation ambiguity is not uniform across frequencies and the illusory perception of tilt has been shown to appear only in the lower frequency range, whereby acceleration at higher frequencies leads to the veridical perception of translation (e.g., Mesland, 1998; Wood, 2002). This may be due to "leaking" in the low pass characteristics of the vestibular system (Mayne, 1974). On the basis of self-motion reports and otolith-ocular responses during off-vertical axis rotation, Wood (2002) identified a crossover frequency around 0.2 Hz at which the ambiguity of the otolith afferent information may be greatest. The coinciding peak in motion sickness around this frequency has subsequently been hypothesised to be the result of this maximal uncertainty regarding the correct frame of reference, i.e., the inability of the vestibular system to resolve whether linear accelerations are the result of tilt or translational motion (Golding et al., 2003; Wood, 2002). This interpretation is also in line with the subjective vertical model according to which the subjective vertical maximally deviates from the sensed vertical at around this frequency (Bles et al., 1998; Bos & Bles, 1998).

The findings reported by Wood (2002) show a remarkable correspondence with the pattern observed in the current study. Despite the absence of angular components in the optic flow pattern, half of the participants in experiment 1 unexpectedly experienced a visual equivalent of the SGI which apparently has not been previously reported. By contrast, within the higher frequency range of experiment 2, this "visual SGI" was reported by two participants for 0.2 Hz oscillation only. Thus, not only was motion sickness most readily evoked at a frequency of 0.2 Hz, the visual SGI also showed the same frequency dependence as the SGI during true linear motion.

According to the multisensory integration hypothesis (Angelaki et al., 1999; Guedry, 1974; Mayne, 1974), to resolve the otolith tilt-translation ambiguity, the brain must rely on information from other sense organs (cf. frequency segregation hypothesis (Mayne, 1974)). An obvious candidate to disambiguate the otolith signal is the concurrent optic flow pattern. Whereas optic flow provides reliable self-motion information under most conditions, the illusory perception of tilt reported in the current study confirms the contention that visual information

may not be as robust as once thought (Gibson, 1950) and is itself prone to misinterpretation. Recent studies into multisensory perception of self-motion have provided evidence that ambiguous visual self-motion information can be disambiguated by other sensory modalities. Illusions of the perceived heading direction, for example, can be reduced by not only additional visual information (Li & Warren, 2000) but also non-visual information including eye- or head movements (Crowell et al., 1998) and whole body tilt (Sibigtroth & Banks, 2001). Bertin and Berthoz (2004) have shown that a vestibular stimulus of short duration steers the self-motion perception of a much longer-lasting visual stimulus. The authors hypothesised that it is the initial percept that is important in self-motion perception tasks involving the reconstruction of travelled trajectories.

However, contrary to the above-mentioned studies in which observers were exposed to ambiguous flow patterns (e.g., optic flow patterns simulating movement along a straight path while making an eye or head movement), the current study suggests that i) even *unambiguous* optic flow patterns may lead to erroneous percepts, and ii) that the perception of the direction of self-motion may gradually change over time and is not entirely determined by the initial percept as hypothesised by Bertin and Berthoz (2004).

Similar to the finding that expectation or "mental set" affects the perception of tilt during true linear acceleration (Mesland, 1998), it is not inconceivable that in the current study, prior experience or expectations may have biased the self-motion percept towards angular self-motion when one considers that arguably the only real-life experience of sustained oscillation occurs whilst being on a swing[3]. In addition, the lack of visual frame or polarity cues (Howard & Childerson, 1994) in

3 A similar "misinterpretation" was reported in a pilot study where individuals were exposed to a 2D random-dot lamellar optic flow pattern moving left-to-right along a straight path parallel to the observer's frontal plane. Instead of perceiving themselves being translated perpendicular alongside a "wall", as one would expect based on the optic flow characteristics, observers perceived themselves rotating around the yaw (z) axis. In a similar vein, prior experience may have biased perception towards rotation, as we are far more familiar with rotational motion than with sustained linear motion perpendicular to the line of sight. Note however that the optic flow due to lateral translation and the optic flow due to rotation about a vertical axis are very similar in small regions when the gaze direction is perpendicular to the direction of self-motion. In particular, rotational flow fields become increasingly lamellar with increasing radius and/or with decreased FOV. Consequently, lamellar flow fields are inherently more ambiguous in comparison with radial flow fields.

the random dot pattern may have allowed for sufficient imprecision in the self-motion system for this illusion to occur. If correct, the visual SGI would therefore not be expected to occur within a virtual environment which includes clear horizontal and vertical structures.

Since the visual SGI was not anticipated, its incidence was not completely documented and hence, these data should be taken as suggestive rather than conclusive. The finding that individuals who reported the SGI also tended to be more susceptible to motion sickness suggests that the SGI could be used as a potential predictor of individual susceptibility. Further investigation of the SGI and subjective vertical may also shed some light on the question why imposed oscillation at 0.2 Hz is most nauseogenic. If the frequency-dependent tilt-translation ambiguity of the otoliths signal is, for as yet unknown reasons, also reflected in the visual self-motion response, one would expect the visual SGI to increase in magnitude (i.e., tilt angle) with decreasing frequency. At the same time, maximum deviation between the sensed and expected vertical would be expected to occur at 0.2 Hz (Bles et al., 1998).

One limitation of the current experiments was that velocity was held constant across frequencies, and thus, acceleration and displacement covaried with frequency. Although an effect of displacement and acceleration on motion sickness cannot be ruled out, the consistent frequency effect found with both constant (Duh et al., 2004) and varying (Lin et al., 2005) peak velocity during rotational motion, suggests the frequency dependence of VIMS to be largely independent of displacement and acceleration. Furthermore, if motion sickness was dependent solely upon the peak velocity of the stimulus, the graph relating motion sickness to frequency would have a gradient of zero. Alternatively, if motion sickness were governed simply by acceleration, motion sickness and frequency would have shown a monotonic relationship. This was clearly not the case, and it appears that, as for true motion sickness, the principal physical characteristics of nauseogenic motion include the frequency (or spectrum in the case of complex motions) and to a lesser extent, the intensity (i.e., acceleration, amplitude) of the motion. However, it would be useful, in future research, to examine relations between motion sickness and a variety of imposed motions, having different amplitudes, accelerations, and motion axes.

Consistent with the findings in the previous chapter, strong correlations between motion sickness and the different vection measures were found. A close temporal correspondence between the time course of vection and sickness ratings was also observed whereby the occurrence of motion sickness was always preceded by vection. Some participants who did not experience motion sickness nevertheless experienced compelling sensations of vection. It is suggested that individual differences in susceptibility to sensory conflict ultimately determines whether or not motion sickness occurs. The current findings are in line with the idea that vection is a necessary precursor of VIMS (e.g., Hettinger & Riccio, 1992).

Finally, as evidenced by the decrease in the proportion of individuals reporting vection over time (figure 4.6 and 4.13), participants slowly adapted to the optic flow pattern. Although adaptation has previously been reported to occur for both linear- (Berthoz et al., 1975; Denton, 1980) and circular vection (Brandt et al., 1974) using constant velocity motion profiles, the current study indicates that adaptation can also occur during oscillating motion. As much as the waterfall illusion or motion aftereffect (MAE) is prevented from occurring during exposure to oscillating expanding-contracting optic flow patterns (Tootell et al., 1995), in the light of neuronal fatigue, oscillating motion would be expected to prevent adaptation from occurring. The finding that adaptation nonetheless occurred may therefore be more readily interpreted in terms of central multisensory fusion processing (e.g., Borah et al., 1988; Ernst & Banks, 2002; Ernst & Bülthoff, 2004; Peterka, 2002; Reymond et al., 2002; Zacharias & Young, 1981) whereby unreliable sensory information is gradually weighted less heavily. Studies into postural control, for example, have shown that standing on a sway referenced platform renders proprioceptive feedback less reliable than during stance on a stable platform, resulting in increased reliance on visual and vestibular sensory feedback (Peterka, 2002; Peterka & Loughlin, 2004). When visual information is then simultaneously perturbed by persistent random moving scenes, the sensory integration process re-weights the incoming sensory information, placing less emphasis on the visual channel. As a result, subsequent visual perturbations have less impact on postural response. It is not unlikely that a similar process is responsible for the vection adaptation observed in the current study in that

individuals, over time, may have been able to determine that vestibular cues were providing veridical self-motion information and therefore relied more heavily on the vestibular system, discounting or vetoing the visual information.

4.10 Conclusion

With the use of sinusoidal horizontal oscillation which has the same peak velocity over the frequency range 0.025 to 1.6 Hz, the level of VIMS peaks within the frequency range 0.2 – 0.4 Hz. It is concluded that the frequency response of VIMS for linear motion differs from that for angular motion, and hence, the crossover hypothesis cannot be extrapolated to linear motion. Instead, VIMS is hypothesised to peak at that frequency where the vestibular system approaches unity gain and, at the same time, the visual self-motion system is sufficiently potent in effect resulting in maximum visual-vestibular conflict.

C_5
Effects of gaze position on VIMS

5.1 Summary

In the previous studies, eye movements and gaze position were controlled by asking participants to fixate a central fixation. Considering that under natural conditions observers shift gaze in order to sample from the environment, the main impetus of the current study was to investigate if, and to what extent, viewing conditions affect motion sickness. A radial optic flow environment was employed, and in view of its spatiotemporal structure, vection magnitude and motion sickness were expected to increase when gaze position was directed away from the focus of expansion. Twelve participants were exposed to an expanding-contracting radial optic flow pattern under four viewing conditions: (i) fixation at the focus of expansion; (ii) fixation at targets located 16 degrees eccentric with respect to the focus of expansion; (iii) consecutive gaze shifting between the focus of expansion and eccentric located targets; (iv) free viewing. Subjective measures of motion sickness and vection were obtained and gaze position was monitored using video-oculography. Compared with the conditions in which participants were free to move their eyes, or fixated at the focus of expansion, forced eccentric gaze significantly increased the level of motion sickness and facilitated vection. In conclusion, optic flow appears to interact differently with different portions of the retina and, in central vision at least, VIMS is influenced by retinal image velocity. Gaze position does affect VIMS.

5.2 Introduction

Differences in viewing conditions are known to affect motion sickness during optokinetic drum stimulation (Flanagan et al., 2002; Stern et al., 1990). However, with this form of display a change in fixation position will not alter the visual stimulus. Furthermore, uniform texture flows, as are seen within optokinetic drums, seldom occur in either real or simulated environments. Other texture flows, such as expanding radial optic flow, which induces a perception of forward self-motion, might be expected to affect motion sickness differently from those which give rise to the sensation of lateral movement. This is because the spatiotemporal structure of radial optic flow is not constant: the local image velocity at the focus of expansion (FOE) is zero and increases with eccentricity. This type of optic flow also produces a different stimulus when gaze position changes. With the FOE centred on the fovea(s), the situation is simulated in which gaze is in the direction of heading, but this is not the case when fixation is eccentric. The issue addressed here was whether there is a difference in nauseogenicity when fixation is at the FOE from when it is away from the FOE, simulating the situation in which the observer shifts gaze in order to sample from the environment.

Previously it has been shown that during exposure to radial optic flow patterns, susceptible participants tended to concentrate their visual attention around the FOE, showed a more limited variability in gaze behaviour, and fixated for longer periods than non-susceptible participants (Turner & Kendrick, 2003). Since sickness was not assessed per-exposure in their study it was not clear, however, whether the limited and inflexible pattern of visual search increased the level of sickness, or whether the occurrence of sickness may have instigated participants to restrict their gaze around the FOE in an attempt to alleviate sickness (Turner & Kendrick, 2003).

Indirect support for the latter interpretation comes from a study by Webb and Griffin (2003). In this study, vection magnitude and motion sickness measures were obtained whilst participants tracked either a single moving dot, or a full screen of laterally moving dots. Although participants reported more vection with full-field stimulation, motion sickness did not significantly differ between the two conditions. The apparent dissociation between vection and motion sickness

led the authors to hypothesise that they were dominated by peripheral and foveal stimulation, respectively. There is strong evidence, however, that this functional foveal-peripheral dichotomy cannot be upheld. First, motion sickness has been reported with foveal vision masked (Diels & Howarth, 2006), and second, central and peripheral stimulation yield comparable effects with regard to vection when they are equated for retinal area and specify a background surface (Howard & Heckmann, 1989; Telford & Frost, 1993). Nevertheless, it cannot be ruled out that central vision[1], rather than foveal vision, plays an important role in the generation of motion sickness. Increased velocity of the stimulus displayed has been shown to lead to an increase in the occurrence of motion sickness (Hu et al., 1989; So et al., 2001), and this may also explain why susceptible participants in Turner and Kendrick's study (2003) restricted their visual attention around the FOE which would have limited retinal image velocity in central vision.

The only previous investigation of the effect of viewing conditions in a radial optic flow environment is that of Sparto et al. (2004). In this study, participants performed gaze shifting tasks in order to locate targets superimposed on a radial optic flow background. The level of motion sickness was found to be lower than that reported during the use of flight simulators or head mounted displays, which led the authors to conclude that gaze shifting is tolerated well. However, short exposure durations within each trial (90 sec), as well as long inter-trial rest intervals (3 min), during which some recovery was likely to have taken place, may limit the validity of this interpretation to short term exposures. Although their experiment was not designed to investigate the effect of viewing conditions as such, it is of interest to note that motion sickness during gaze shifting tended to be slightly higher than during central fixation.

To investigate whether viewing conditions affect VIMS we have evaluated it in four situations: (i) gaze position fixed at the FOE; (ii) gaze position fixed on a position eccentric with respect to the FOE; (iii) consecutive gaze shifting between the FOE and eccentrically located target positions; (iv) spontaneous

[1] As pointed out by Warren and Kurtz (1992), there is little agreement in the literature on what is meant by "central" and "peripheral" vision. Following Warren and Kurtz, we here consider displays up to 20° in diameter to stimulate central vision

unrestricted gaze. In addition to subjective measures of motion sickness, we obtained vection data and eye movement recordings using video-oculography. On the basis of previous studies, eccentric gaze position (conditions ii and iii) was hypothesised to exacerbate VIMS in comparison with the other two conditions.

5.3 Methods

Participants

Twelve healthy Japanese male participants with a mean (± SD) age of 22.58 (± 1.31) years gave their informed consent to participate in the study, following its approval by the Waseda University Ethical Advisory Committee. All participants had intact vestibular function and were not receiving any medication.

Translations

All questionnaires and written instructions had been translated from English into Japanese by experienced bilingual experts. To ensure validity, questionnaires were translated back into English and subsequently crosschecked.

Apparatus

Participants were seated in a dark room. The head of each participant was stabilised by means of a head/chin rest. The stimuli were presented on a rear projection TV (ELS-57P, Epson, Nagano, Japan; screen size 126 x 71 cm, 1024 x 768 pixels), at a viewing distance of 48 cm. The visual field was 68.9° (h) x 52.3° (v) of visual angle due to the physical restrictions imposed by the eye tracker. Stimuli were presented at a rate of 60 Hz by means of an Intel Extreme Graphics card (64Mb), which was controlled by Matlab (version 6.5) running the Cogent Graphics Toolbox. Acoustic localisation cues were masked by pink noise (75 dB) transmitted to earphones worn by the participant.

Eye movements were measured continuously throughout exposure to the visual stimulus using an eye-tracking system, which was composed of two CCD

cameras attached to goggles (ET-60H, New Opt Co., Kanagawa, Japan). Eye movement recordings were processed using an image analysis system programmed using PC software (LabView Vision, National Instruments, USA), which enabled analysis of horizontal and vertical eye positions from the relative position of pupil centre.

Stimulus

The visual stimulus consisted of an expanding-contracting random dot optic flow pattern simulating oscillating translational motion in the anterior-posterior axis at 0.2 Hz (average optical peak velocity 26°/sec), which has previously been shown to be a particular provocative stimulus (Diels & Howarth, 2006). The display consisted of 500 white dots each with a luminance of 124 cd/m^2 randomly positioned on a black background of 0.51 cd/m^2 (Figure 5.1a). See Appendix 28 for further details on the visual stimuli.

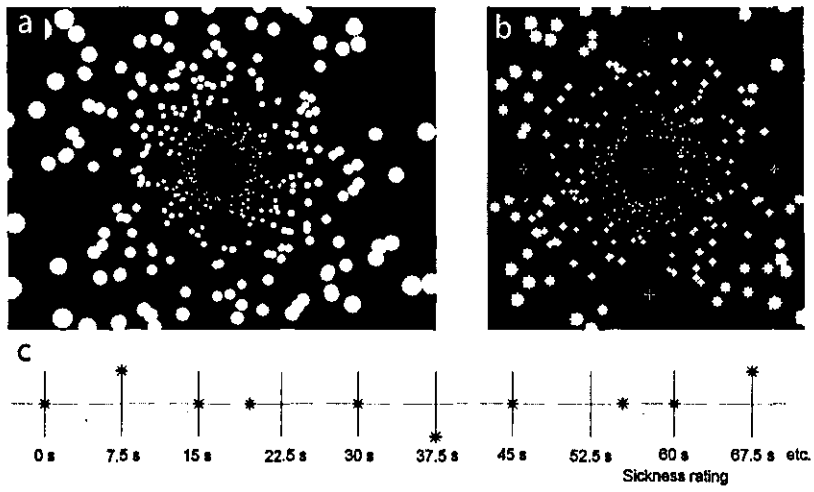


Fig 5.1 (a) Sample frame of the radially expanding-contracting optic flow pattern. The pattern oscillated at a frequency of 0.2 Hz. (b) Centre sample frame. (c) Order of fixation position (asterisk) in condition GS.

Dot velocity and size varied exponentially as a function of their simulated location in depth. Dot size at the eye ranged from 0.12° at the middle to 4.53° at the periphery. Five fixation crosses were superimposed on the optic flow pattern: a centre fixation cross and four eccentric fixation crosses 16° to the left, right, below and above the centre fixation cross. Behind each of the five fixation

points, a black disc subtending 7.6° of visual angle was added in order to reduce reflexive eye movements as well as to keep foveal stimulation constant across different conditions (Figure 5.1b).

Procedure

Four different viewing conditions were created: (i) Central Fixation (CF): during the trial participants were instructed to fixate the central fixation cross. (ii) Fixation Eccentric (FE): participants were instructed to keep fixating one of the four eccentric fixation crosses throughout the experiment. The number of participants fixating each of the fixation crosses was balanced across conditions with three participants for each fixation cross. (iii) Gaze Shifting (GS): participants were asked to move fixation from the central cross to each of the five fixation crosses in a fixed sequence. An auditory cue (750 Hz, 200 ms duration) was presented to serve as the go-signal to perform a saccade to the eccentric fixation cross. After 7.5 sec, another auditory cue (500 Hz, 200 ms duration) was presented to serve as the signal to return to the central cross. After a further 7.5 sec, the next eccentric cross in the sequence was fixated, and so on. The sequence followed a counter clockwise direction, and 10 full circle repeats were performed (Figure 6.1c). (iv) Free View (FV): participants were allowed to look anywhere on the screen. They were also instructed not to stare through the screen. The stimulus presentation was identical in all four conditions, and the auditory cues were also present in all four conditions.

Trials for each of the four conditions lasted for 10 min, and were separated by at least 24 hrs to limit any habituation to the stimulus. To avoid possible circadian rhythm effects, each session took place at the same time of day. A repeated measures design was used with each participant acting as his/her own control. To minimise order effects, the order in which the four conditions were presented was balanced using a 4x4 Latin square design.

Prior to the first session, participants received written instructions and a demonstration. Vection was defined as a compelling feeling of self-motion, such as "the feeling you get when a train moves next to you and you mistake it for your own motion." To ensure participants differentiated between object- and

self-motion, they were asked during this briefing to view a vertically translating optic flow pattern until a compelling sensation of vertical linear self-motion was reported. This typically occurred after about 15 seconds. When they indicated that they fully understood the task, the eye tracker was calibrated and the experiment commenced.

Motion sickness measures

Participants rated the severity of their motion sickness every minute on Bagshaw and Stott's (1985) sickness scale (1 no symptoms; 2 mild symptoms, but no nausea; 3 mild nausea; 4 moderate nausea). To avoid participants making any head movements, they were asked to indicate the level of sickness with their left hand. The experiment was stopped at malaise rating 4 or after 10 min, whichever was the sooner. Participants who reached a sickness rating of 4 and stopped before 10 min were assigned continuation values of 4. All the participants were initially symptom-free and the measures of interest were the time for participants to first report a sickness rating of 2 ('time to sickness rating 2') and 3 ('time to sickness rating 3'), the maximum sickness rating, and the sum of the sickness ratings over the 10 min exposure duration ('accumulated sickness rating'). If no symptoms were reported, an accumulated sickness rating and symptom onset time of 11 was recorded.

In addition, motion sickness symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). Each participant completed the SSQ both before and after each session. Measures of interest were the change (post – pre exposure score) in the SSQ total scores and the SSQ subscores nausea, oculomotor, and disorientation.

Vection measures

To evaluate the time course and total duration of vection, participants were instructed to press a button whenever they experienced vection, and to keep it depressed for as long as they experienced it. Vection onset latency was defined as the time it took for subjects to first press the button. Vection duration was defined as the percentage of the total exposure time that vection was reported.

Vection magnitude was assessed post exposure by asking participants to rate their experience in terms of the following question: 'Whilst watching the moving images, did you get the feeling of motion? Did you experience a compelling sensation of self-motion as though you were actually moving?' The endpoints of the 7-point Likert scale were anchored as 'not at all' (1) and 'very much so' (7) (after Prothero, 1998).

Eye movement measures

The eye movements recorded in condition FV were analysed using three different dependent variables. These were the variance in eye gaze coordinates along the horizontal and vertical meridians, and the average path length (the overall sum of displacement divided by the duration of exposure).

To identify the areas of the visual stimulus to which participants were attending, recordings of the eye positions over the trial were overlaid by a grid with a resolution of 2 x 2 degrees of visual angle. Based on the total amount of time spent in each of the squares, contour maps were created representing the areas where participants' visual attention was focussed, as well as the amount of time spent there expressed as the percentage of the total exposure duration.

Susceptibility

Based on Turner and Kendrick's (2003) observation that gaze behaviour varies as a function of susceptibility, participants in condition FV were separated into susceptible and non-susceptible groups on the basis of their maximum sickness ratings. The eye movement data of one participant could not be used for technical reasons, and these were discarded in the analysis. Three participants comprised a higher susceptibility group (max sickness rating ≥ 3), whereas the remaining eight participants formed a lower susceptibility group (max sickness rating ≤ 2).

Statistical analysis

Data analysis was performed using the software package SPSS (version 13). An initial analysis of the data revealed that no significant order effect was present (Appendix 27). For all groups of non-parametric dependent variables (accumulated sickness ratings, vection magnitude ratings), data were compared using Wilcoxon Signed ranks tests. For all groups of parametric dependent variables (symptom onset time, vection onset, vection duration, eye movement data) that passed the tests for normality, data were compared using Tukey's HSD tests. Correlations between different groups of measurements were assessed by Spearman's rho.

5.4 Results

Sickness ratings

Table 5.1 shows the number of participants reaching each sickness rating before the 10 min maximum time cut-off. Because of the severity of motion sickness symptoms experienced, one participant requested termination of the trial before the end in conditions GS, FV, and CF. One participant requested termination of the trial in condition FE and a further participant stopped during condition GS.

TABLE 5.1. NUMBER OF SUBJECTS REACHING EACH SICKNESS RATING BEFORE MAXIMUM 10-MIN CUT-OFF. THE TRIAL WAS TERMINATED IF A RATING OF 4 WAS REACHED.

	Condition			
Sickness rating	CF	FE	GS	FV
2	8/12	9/12	9/12	9/12
3	3/12	5/12	4/12	3/12
4	1/12	1/12	2/12	1/12

The time-course of mean sickness ratings is shown for each of the four conditions in figure 6.2 (see appendices 20-23 for individual data). Conditions FV and CF produced the lowest mean sickness ratings while conditions FE and GS, in which peripheral fixation was forced, resulted in the highest ratings.

Although data were not collected beyond 10 min in this study, two participants reported feeling slightly nauseous for more than 2 hours after being exposed to both condition GS and FE.

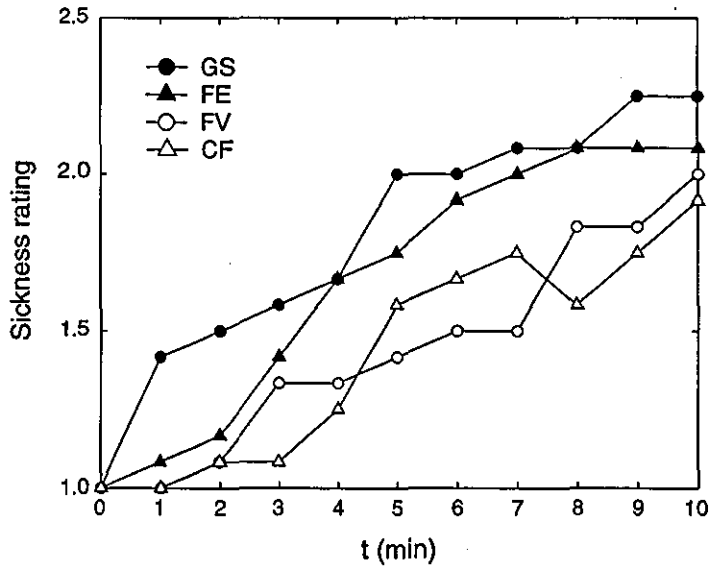


Fig 5.2 Mean sickness rating as a function of time for each of the four conditions. Filled symbols represent the two conditions where fixation was away form the FOE.

Figure 5.3a shows the mean accumulated sickness ratings for each condition. The mean accumulated sickness rating was significantly higher in condition GS (19.83) than in condition CF (16.17) and condition FV (15.83) ($p < 0.05$, Wilcoxon). The mean accumulated sickness rating in condition FE (18.50) was higher compared with condition FV ($p < 0.05$, Wilcoxon) and condition CF, although the latter difference failed to reach the level of significance required ($p = 0.079$). The effect of viewing condition is particularly evident after separating the participant sample into a susceptible and non-susceptible group based on their mean accumulated sickness rating over the four conditions. This is shown in figure 5.3b. Forced peripheral fixation (i.e., FE and GS) substantially increased the level of motion sickness in the susceptible group.

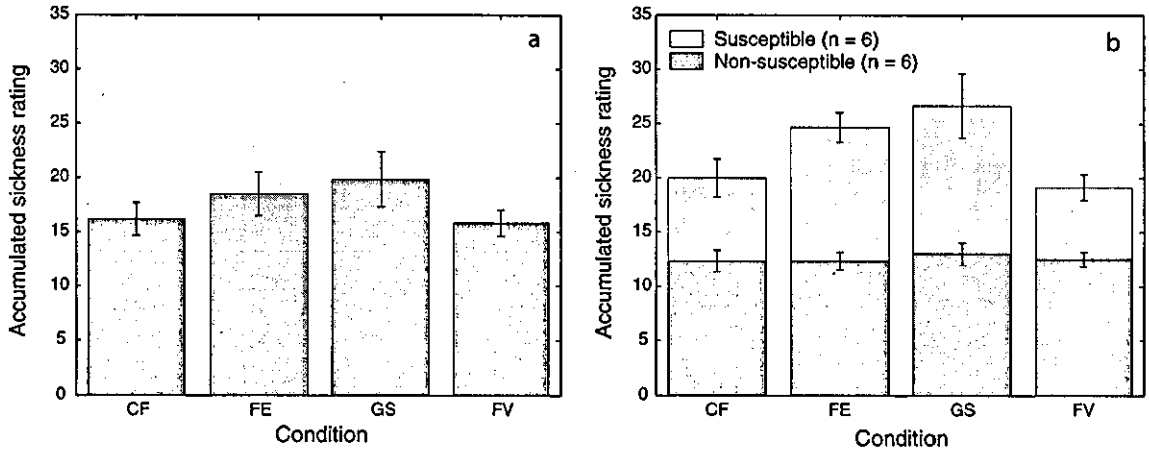


Fig 5.3 (a) Mean (± SEM) accumulated sickness rating for each condition. (b) Mean (± SEM) accumulated sickness rating for each condition as a function of susceptibility.

Symptom onset times

Due to the large number of participants reaching the 10-min cut-off without reporting any symptoms, times to sickness ratings 2 and 3 were not normally distributed, and non-parametric statistical tests were employed. Figure 5.4a and b show the times to sickness rating 2 and 3, respectively. It can be seen that onset times tended to be shorter during forced eccentric fixation (FE and GS). Wilcoxon signed ranks tests demonstrated that time to sickness rating 2 was significantly shorter in condition GS than in condition CF ($p < 0.05$). Time to sickness rating 3 was significantly longer in condition FV than in condition FE ($p < 0.05$).

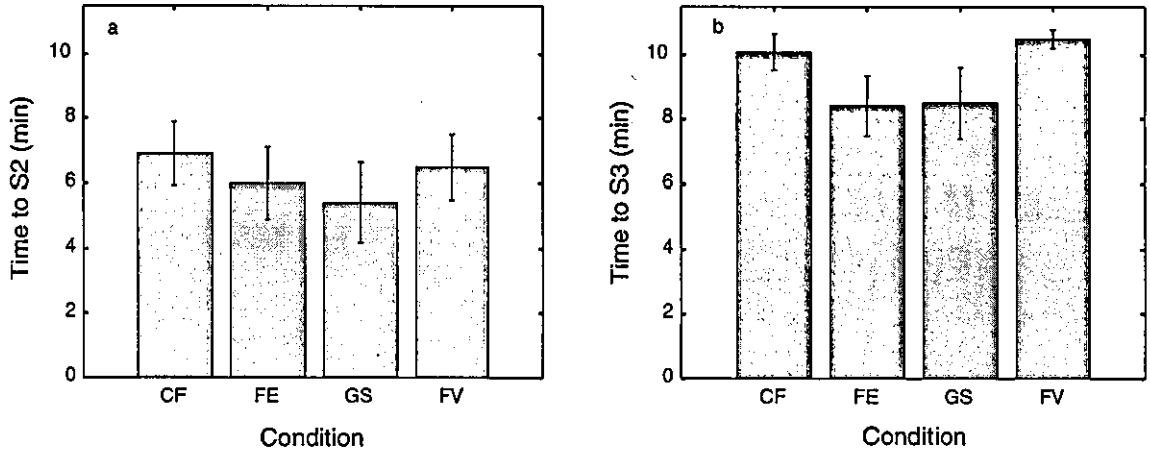


Fig 5.4 (a) Mean (± SEM) time to sickness rating 2 (S2). (b) Mean (± SEM) time to sickness rating 3 (S3).

Simulator Sickness Questionnaire (SSQ)

Figures 5.5a-d show the SSQ total scores and the SSQ N, O, D subscores, respectively. Except for the N subscore, SSQ scores tended to be marginally higher in condition FE compared with the other conditions. None of the differences was found to be significant however.

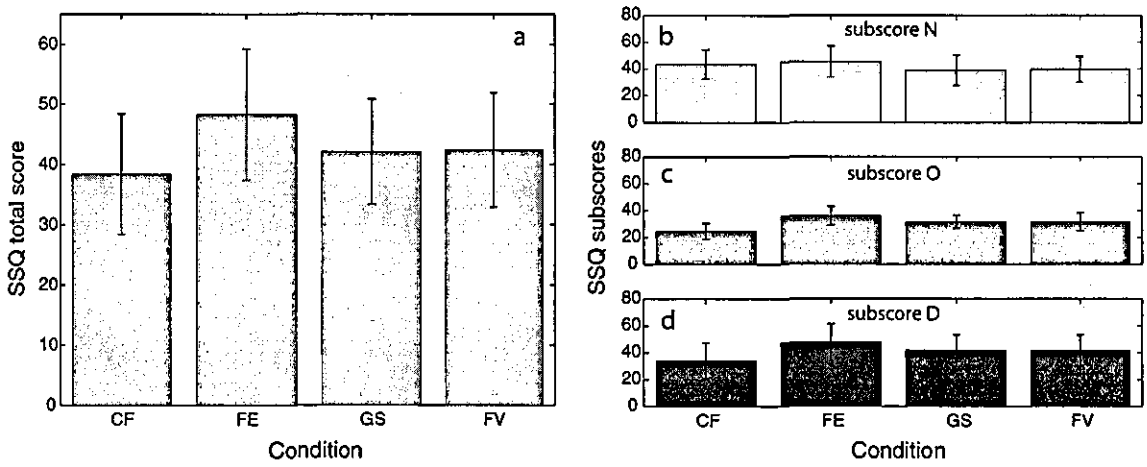


Fig 5.5 Mean (± SEM) SSQ total scores (a) and SSQ nausea, oculomotor, and disorientation subscores (b-d) for each condition.

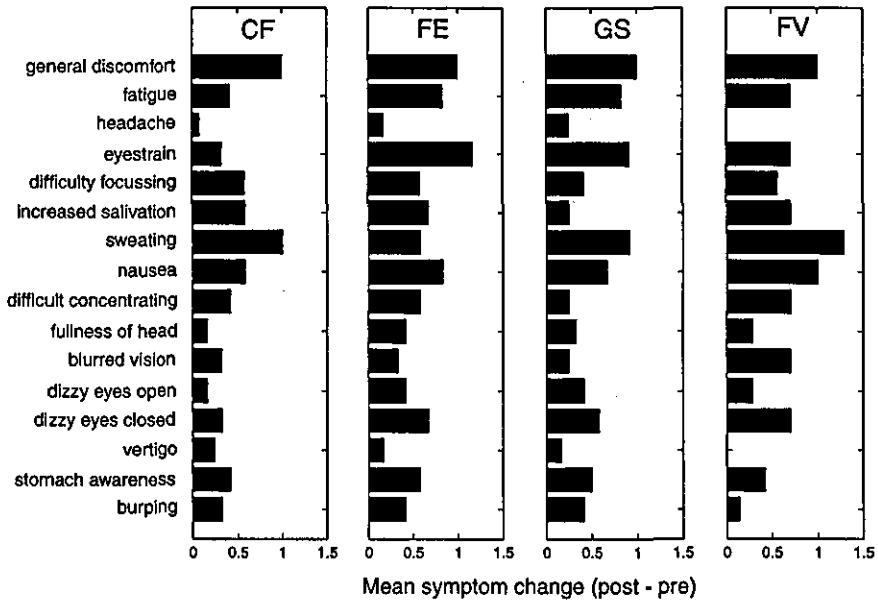


Fig 5.6 Mean change (post – pre score) in symptom severity of individual symptoms for the four conditions.

The mean changes (post - pre score) in symptom severity of the individual SSQ symptoms, are displayed in Figure 5.6. The largest changes were observed for the symptoms general discomfort, fatigue, eyestrain, sweating, and nausea.

Vection

Eleven of the 12 participants experienced linear vection in the direction opposite that of the display motion in all of the four conditions. One participant reported vection and mild symptoms in condition GS only. This may have been a primacy effect as the participant was exposed to condition GS first.

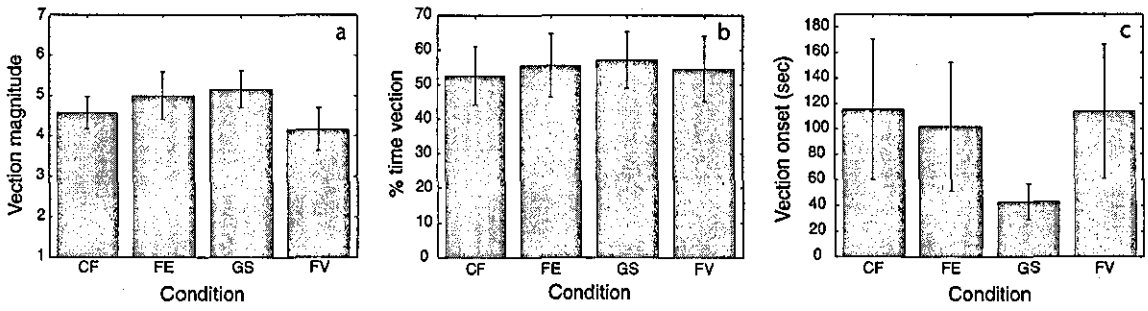


Fig. 5.7 Mean (± SEM) vection magnitude rating (a) vection onset time in seconds (b) and percentage of time vection was experienced (c).

Mean vection magnitude ratings (figure 5.7a) were higher during forced eccentric fixation (conditions FE and GS) than in conditions CF and FV. Although none of the differences were statistically significant, in retrospective questioning ten of twelve participants reported vection magnitude to increase with gaze eccentricity (i.e., conditions FE and GS). A similar trend was observed for vection duration (figure 5.7.b), which was marginally higher in conditions FE and GS, compared with conditions CF and FV although these differences were not statistically significant. Mean vection onset time (figure 5.7c) was shortest in condition GS, followed by condition FE, FV, and CF. The means were heavily influenced by the fact that on trials in which no vection was reported, onset times were assigned values equal to the trial duration, 600 s. When these trials are excluded, the means become 43.1 s (GS), 56.7 s (FE), 69.4 s (FV), and 71.7 s (CF). Gaze eccentricity thus slightly reduced the onset

times of vection when it occurred (i.e., GS, FE < CF, FV) although these differences were not statistically significant.

Mean sickness ratings and the proportion of participants reporting vection over time in each condition are shown in figure 5.8. It can be seen that in all four conditions vection and motion sickness gradually increased over time. Inspection of individual data showed that those individuals reporting motion sickness also reported vection, which consistently preceded the occurrence of motion sickness symptoms. On the other hand, vection was reported by some participants without a concomitant increase in motion sickness symptoms.

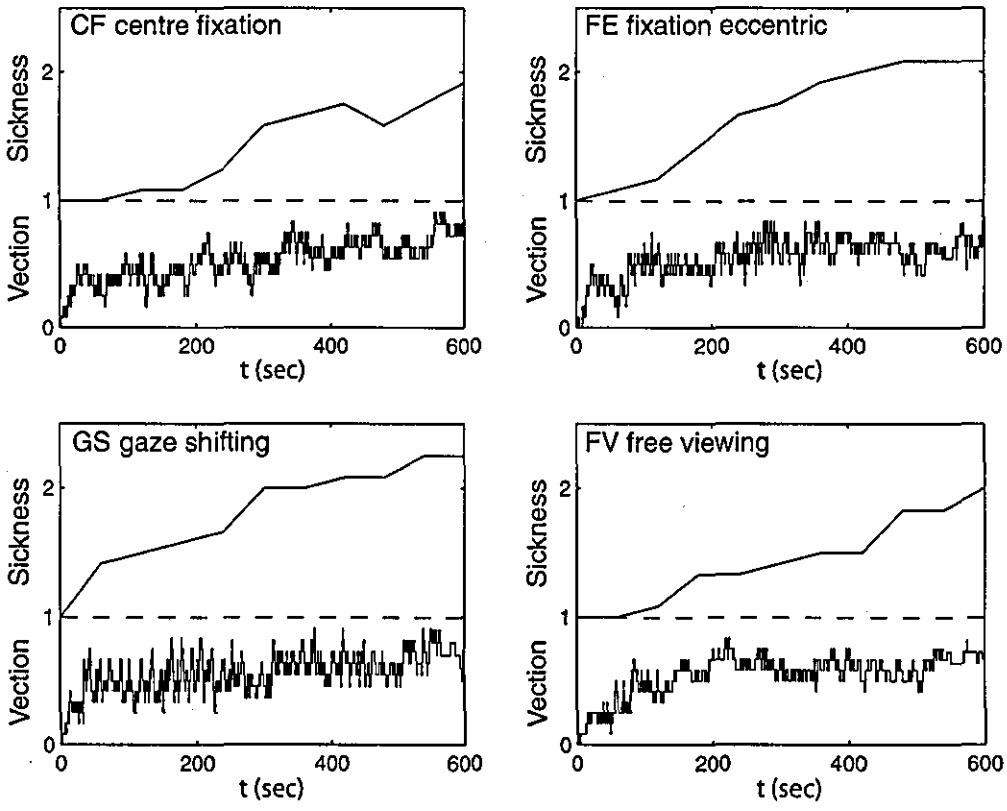


Fig. 5.8 Mean sickness ratings and proportion of participants reporting vection over time for each condition.

Table 5.2 shows the Spearman's rank correlations between the maximum sickness ratings and vection magnitude, duration, and onset times for each of the four conditions and pooled over the four conditions. All three vection measures were strongly correlated with maximum sickness ratings. In comparison with less susceptible participants, those susceptible to motion

sickness tended to report higher vection magnitude ratings, for a longer period of time as well as earlier.

TABLE 5.2 SPEARMAN CORRELATION COEFFICIENTS FOR MAXIMUM SICKNESS RATING AND VECTION MAGNITUDE, DURATION, AND ONSET FOR EACH CONDITION INDIVIDUALLY AND POOLED.

Condition	Vection magnitude	Vection duration (%)	Vection onset (sec)
CF	$r_s = .530$	$r_s = .515$	$r_s = -.563$
FE	$r_s = .627^*$	$r_s = .628^*$	$r_s = -.321$
GS	$r_s = .422$	$r_s = .598^*$	$r_s = -.587^*$
FV	$r_s = .773^*$	$r_s = .528$	$r_s = -.611^*$
Pooled	$r_s = .599^*$	$r_s = .661^*$	$r_s = -.905^*$

* Significant at the 5% level

Eye movements

On- and off-line inspection of the eye movement data for conditions CF, FE, and GS indicated that all participants complied with the experimental protocol, i.e., in each of the three conditions deviation from the target position (i.e., fixation cross) was within ± 4 degrees of visual angle.

In the first part of the analysis of the eye movement recordings in condition FV, each measure was correlated with the accumulated sickness rating. Although non-significant, a consistent trend was found in that accumulated sickness ratings were negatively correlated with horizontal axis variance ($r_s(11)= -.336$, $p= .313$), vertical axis variance ($r_s(11)= -.221$, $p= .514$), and average pathlength ($r_s(11)= -.378$, $p= .252$).

Figure 5.9 shows contour maps of average gaze position in condition FV for the non-susceptible (a) and susceptible group (b). For both groups, gaze position was limited to an area with a radius of approximately 6 degrees around the FOE (centre display) during 75% of the total exposure duration, of which 50% was concentrated in an even smaller area, indicated by the dark grey area.

The difference between the groups becomes more apparent when gaze stability is analysed over the time period of the trial. Figure 5.9c and d show the mean standard deviations of horizontal (x) and vertical (y) eye position (degrees), respectively, over time (1 min time window) for the susceptible and non-susceptible group. Unlike the non-susceptible group, participants in the

susceptible group showed a lower variability in gaze position at the onset of the trial, but tended to increase variability in both horizontal and vertical scanning as the trial progressed.

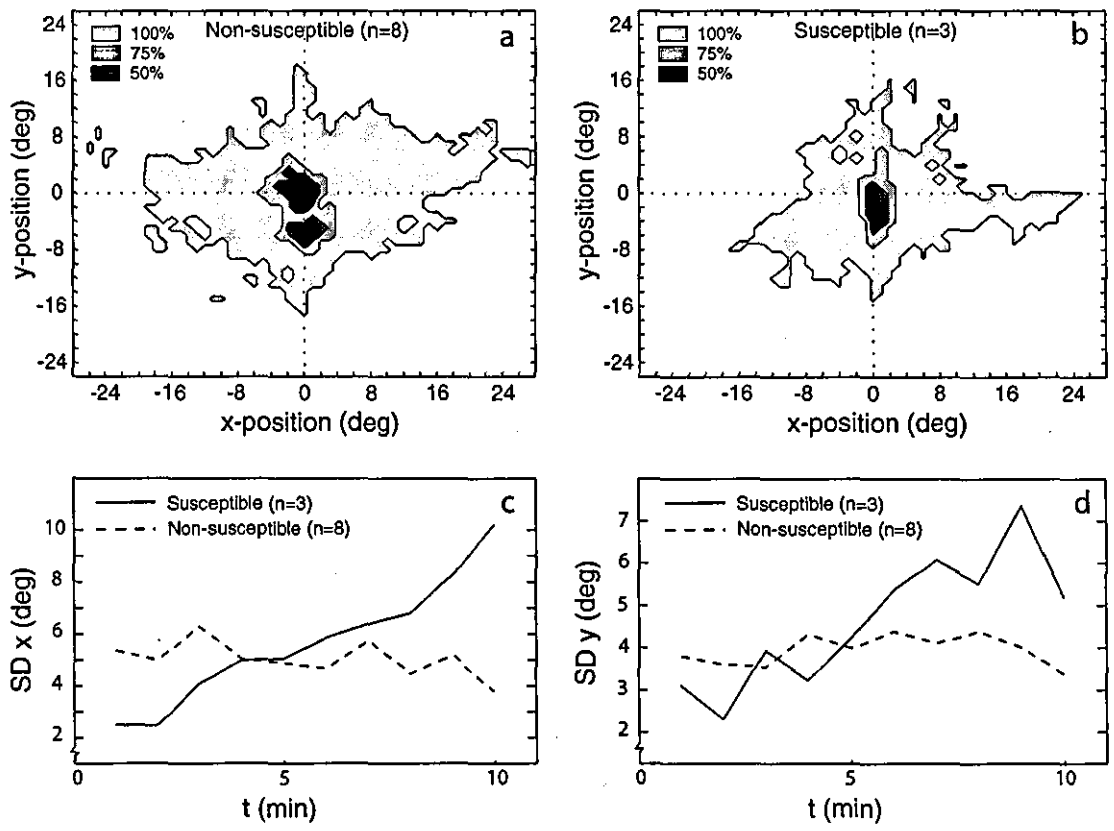


Fig 5.9 Mean variation in eye position in the free viewing condition (FV) over the whole trial. Top row: Contour map of average gaze position for the (a) non-susceptible and (b) susceptible group. Areas indicate the percentage of the exposure duration that gaze position was in corresponding area. Bottom row: Time course of standard deviations (SD) of (c) horizontal and (d) vertical eye position in degrees as a function of susceptibility.

To further examine the relationship between the variability in gaze position and motion sickness, the ratios of the summed standard deviations between minute 1-4 and minute 6-9 were calculated for both horizontal and vertical directions, and were subsequently correlated with the accumulated sickness ratings for all 11 participants for whom eye movement data was available. Positive correlations between the accumulated sickness rating in condition FV and the ratios for the horizontal ($r_s(11)= .423$, $p= .195$) and vertical directions ($r_s (11)= .621$, $p= .042$), indicate that those participants who reported more motion sickness tended to increase their variability in gaze position over time.

5.5 Discussion

The aim of this study was to investigate the effect of gaze position on VIMS in radial optic flow environments, and it was hypothesized that eccentric gaze position with respect to the FOE would exacerbate VIMS. Despite relatively short exposure durations (10 min), this clearly occurred. In comparison with conditions in which participants were free to move their eyes or were asked to fixate the centre fixation cross (FV and CF, respectively), forced eccentric gaze position (FE and GS) slightly decreased vection onset times, increased vection magnitude ratings and duration, and significantly exacerbated the level of motion sickness as assessed by Bagshaw and Stott's sickness rating scale.

The effect of gaze position was however not reflected in the SSQ scores which did not significantly differ across conditions. This would suggest the SSQ to be a less sensitive measure of motion sickness than the measures based on per-exposure assessment such as the accumulated sickness rating and times to symptoms onset. The SSQ is a composite score, however, which is made up of a number of questions and each may have different cultural meanings. It is thus quite possible that the discrepancy between the measures is due to the fact that the SSQ has not been validated for a non-English population. The finding that half of the participants reported mental depression[2] in at least one of the four conditions, in contrast to none of the predominantly Caucasian participants in al of the previous studies, illustrates the need for cultural validation rather than mere translation of instruments such as the SSQ. In this context, it is also of interest to note that in the process of translating the MSSQ[3] into Japanese, the question with regard to experience with (playground) roundabouts was initially omitted by one of the translators. The reason for this was that roundabouts are virtually unknown in Japan, and the item was subsequently not considered relevant by the particular translator. Whereas omission or a zero response to this particular item may not have dramatically affected the MSSQ score, it illustrates that with regard to the subjective assessment of motion sickness such as the MSSQ and SSQ, further validation for non-Caucasian populations is

2 Note that the MSQ (Kennedy et al., 1989) was employed consisting of 28 symptoms, 16 of which are used to calculate the SSQ scores (Kennedy et al., 1993). Mental depression does not feature in the SSQ.

[3] The MSSQ results will be separately discussed in chapter 7 in the context of the predictive validity of this questionnaire.

warranted. Recently, this was also pointed out by Klosterhalfen et al. (2005) who showed in their study that MSSQ ratings given by Chinese participants did not reflect their higher susceptibility during subsequent cross-coupled Coriolis tests. Considering these limitations of the SSQ data, the remaining discussion is based on the per-exposure motion sickness measures.

Returning to the discussion regarding the exacerbating effect of forced eccentric gaze position, the finding that motion sickness during gaze shifting (GS) did not differ from the level reported during eccentric fixation (FE), indicates no surplus effect of the eye movements, unless it is balanced by an ameliorating effect of the recurrent return to the central area of the display. The finding further indicates that the elevated level of sickness in condition FE does not pertain to maintained eccentric gaze position as such. No difference was found also between the central fixation condition (CF) and the free viewing condition (FV). However, this is hardly surprising because the eye movement records showed that in the FV condition, gaze position was largely limited around the FOE.

The present results suggest that the position and direction of the optic flow structure interacts with the exposed retinal area in the generation of VIMS. Local image velocity increases towards the periphery in radial displays, and because of this, one possible explanation for the observed effect is the increase in retinal image velocity in central vision during fixation away from the FOE. Apart from its dominant role in the adaptation of the vestibulo-ocular reflex (Shelhamer et al., 1994) and the control of optokinetic nystagmus (Howard & Ohmi, 1984), retinal image velocity in central vision may also prove to be the most significant signal driving VIMS. However, if velocity is unimportant then the results are also consistent with potency increasing away from the fovea. This is because the visual stimulus is of fixed size, and as fixation at the FOE and eccentric fixations allow different portions of the retina to be stimulated, such inhomogeneity of the retina would produce the results seen.

A further factor that may be relevant is that heading judgements are less accurate in peripheral than in central vision with radial flow fields. Disparities between gaze and heading direction as small as 10° have been shown under some circumstances to reduce performance to near chance level (Warren & Kurtz, 1992). In the current study, it is reasonable to assume that heading

accuracy and precision during eccentric viewing conditions was also impaired. While the relationship between heading performance and motion sickness is not evident, disparities between gaze and heading direction could have compromised information of near future motions, thereby possibly deteriorating the ability to anticipate incoming sensory cues, which, in turn, has been shown to be associated with increased motion sickness (Lin et al., 2005; Rolnick & Lubow, 1991; Stanney & Hash, 1998).

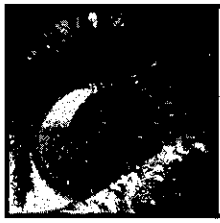
A possible confounding factor in the current study is the fact that eccentric fixation not only resulted in an increase in motion sickness, but also vection. The strong correlations between vection and motion sickness further indicate that the participants who reported higher levels of motion sickness were those who also reported more vection. However, it is unclear whether motion sickness is caused by vection or the sensory conflict that often, but not necessarily, accompanies vection. For example, compelling sensations of vection are reported during exposure to a constant velocity radial optic flow pattern without concomitant motion sickness (Diels & Howarth, 2005). This vection should be no different from that experienced during true motion at constant velocity, and it follows that vection does not necessarily reflect sensory conflict. Alternatively, the finding that motion sickness is absent by some participants who still experienced vection may indicate that some individuals are insensitive to sustained conflict. Thus, whereas vection is often accompanied by the occurrence of motion sickness, the two may be independent.

Two factors may have facilitated the occurrence of vection during the peripheral fixation condition in the current study. First, since vection has been shown to increase with image velocity (Brandt et al., 1973; Dichgans & Brandt, 1978; Lestienne et al., 1977), the increased vection during peripheral fixation may be explained by the increased retinal image velocity in central vision. Second, motion of seen parts of the own body or external objects relative to the scene are also known to facilitate vection (Brandt et al., 1975; Howard & Howard, 1994; Mergner et al., 2000). In the present study, the visible parts of the orbital rims, as well as the visible parts of the eye tracker increased with gaze eccentricity, which may have accounted for the observed differences.

The negative correlations between motion sickness and the different eye movement measures (i.e., horizontal and vertical axis variance, average pathlength) would appear to be consistent with previous findings by Turner and Kendrick (2003) and suggest that susceptible individuals show less variability in gaze behaviour than non-susceptible individuals. However, an unexpected finding was that susceptible participants tended to increase gaze variability over time and so this consistency was only true during the early stages of the trials, and the opposite was seen in the later stages. If it is, indeed, the case that eye movements per se do not increase symptoms, then one would expect those participants to experience greater symptoms towards the end of the trial because of the greater time they spent fixating in the periphery of the stimulus. This was seen to happen.

5.6 Conclusion

In summary, it was shown that gaze eccentricity with respect to the FOE increases vection and VIMS, and because of the interaction between the optic flow structure and the exposed retinal area, it is suggested that VIMS is affected by retinal image velocity in central vision.



C_6
VIMS during single- and dual-axis motion

6.1 Summary

The majority of studies into VIMS either use complex motion scenarios or are limited to single-axis motion. This study compared VIMS during single- and dual-axis motion. Twelve participants were exposed to (i) oscillating roll motion, (ii) linear motion in the anterior-posterior axis, and (iii) spiral motion, i.e. the summed direction of both of these flow vectors. Increased sensory conflict during exposure to spiral motion was hypothesised to increase the level of motion sickness compared with exposure to its constituent motion patterns in isolation. Unexpectedly, spiral motion was not found to be more nauseogenic than either of the two single-axis motion patterns and this was consistent across participants. This finding argues against the magnitude of VIMS being determined by simple summation of the provocative stimuli.

6.2 Introduction

In the previous chapters, VIMS was investigated using optic flow patterns simulating single-axis ego motion. Optokinetic drum experiments conducted by others similarly typically present rotational motion along a single axis. Many real world scenarios, however, are characterised by displays of optic flow simulating complex patterns of self-motion. Hence, the question addressed in this chapter is how VIMS varies as a function of multi-axis motion stimulation.

The severity of motion sickness is assumed generally to be monotonically related to the degree of conflict in one or more sensory channels (Oman, 1982, 1991; Reason, 1978). Findings such as the tendency of visual-field rotation around earth-horizontal axes (i.e. pitch and roll) to be more provocative than rotation around the earth-vertical axis (i.e. yaw) (Lo & So, 2001; Ujike et al., 2004; Yang & Pei, 1991) are usually explained by differences in the degree of sensory conflict. The absence of an expected signal from the semicircular canals results in sensory conflict during visual-field rotation in all three rotational axes, but during rotation of the visual stimulus around earth-horizontal axes (unlike earth-vertical axes) there is additional conflict due to the expected, but absent, signal from the otoliths.

Further support for a monotonic-additive effect of the degree of conflict on motion sickness comes from optokinetic drum studies in which the orientation of the stripes is systematically altered. In a study by Andre et al. (1996), observers were exposed to 60°/s optokinetic drum stimulation with the inner wall of the optokinetic drum covered by either vertical stripes or off-vertical stripes tilted 15° in the direction of drum movement. Under the tilted drum condition, in which the stripes moved down and to the right, participants reported a complex vection with both a horizontal and vertical component. As predicted, the added mismatch between the visual vertical and the vestibular vertical in the tilted condition significantly increased gastric tachyarrhythmic activity, although no significant differences were found in subjective measures of motion sickness. More recently, Bubka and Bonato (2003) conducted a similar experiment in which observers were exposed to 60°/s optokinetic drum stimulation with the drum either aligned to the earth-vertical axis (yaw), or tilted relative to the axis

of rotation (5° and 10° tilt). In this study, drum tilt resulted in a significant increase in reported motion sickness.

Although these studies provide some support for the notion that VIMS and the degree of conflict show a monotonic relationship, it should be noted that these studies are limited to rotational motion. As evidenced by the finding that the frequency dependence of VIMS may differ between rotational and translational motion (see Chapter 4), it cannot be automatically assumed that findings based on rotational motion can be extrapolated to different motion scenarios, including translational motion. Hence, the hypothesis of a monotonic additive effect of sensory conflict on VIMS for combined translational and rotational motion was tested.

Stationary observers were exposed to optic flow patterns simulating oscillating roll motion, oscillating linear motion in the anteroposterior axis, and the summed direction of both flow vectors, i.e. spiral motion. During oscillating linear motion, conflict is caused by the absence of corresponding signals from the otolith organs, whereas oscillating roll motion results in a semicircular- and otolith-visual conflict, as described above. Predicated on an additive model, dual-axis motion was hypothesised to result in higher levels of VIMS compared with single-axis motion because of the greater total conflict. Rotational and translational motion patterns of equal nauseogenicity were identified in a pilot study, hence, no differences were expected between the two single-axis motion patterns.

6.3 Methods

Subjects

Twelve healthy participants (5 female, 7 male) with a mean (± SD) age of 26.08 (± 6.13) years gave their informed consent to participate in the study, following its approval by the Loughborough University Ethical Advisory Committee. All had intact vestibular function, none were receiving any medication, and all had normal or corrected-to-normal vision.

Apparatus

Trials took place in a dark room, and each participant had their head stabilised by means of a head/chin rest. The visual stimulus was produced using Matlab (version 6.5; Cogent Graphics Toolbox) controlling a Matrox Millennium P750 graphics card (64Mb) running on a DELL GX computer. The images were backprojected onto a tangent screen (190 cm x 145 cm) with a Hitachi CP-X958W/E projector (1024 x 768 pixels). To occlude the edges of the screen and other peripheral features, participants wore goggles, which limited the visual field to 65° (h) x 59° (v) of angle. Acoustic localisation cues were masked by pink noise (75 dB) transmitted to earphones worn by the participant. In addition, auditory alerting bleeps of different frequencies (500, 750, and 1000Hz at 100dB) were played at random intervals throughout the exposure duration. Communication with the participants during exposure was via a microphone.

Stimuli

The visual stimulus consisted of 500 moving white filled-in circles (10.82 cd/m^2) on a black background (0.35 cd/m^2) (see figure 2.2). All stimuli were presented at a refresh rate of 60 Hz. For technical reasons, there were no dots at the very centre of the visual scene, and as a consequence, there was a black disc subtending 8.75° of visual angle. A red (fixation) dot (0.57° of visual angle) was projected at eye height in the centre of the screen.

Three optic flow patterns were used:

Condition R: oscillating roll motion was simulated by sinusoidal rotation of the random dot pattern around the anteroposterior axis at a frequency of 0.2 Hz (peak-to-peak amplitude of 120°, average angular velocity of 48°/sec).

Condition FB: radially expanding/contracting displays simulated sinusoidally oscillating forward and backward linear motion along the anteroposterior axes through a 3D cloud of randomly positioned dots. Dot velocity and size varied exponentially as a function of their simulated location in depth. Dot size at the eye ranged from 0.12° at the middle to 4.53° at the periphery. The display oscillated at a frequency of 0.2 Hz with an average peak angular velocity of 34°/sec.

Condition RFB: summation of the flow vectors in condition R and FB simulated spiral motion, i.e., simultaneous in-phase roll and forward-backward motion. See Appendix 28 for further details on the employed visual stimuli.

Procedure

Participants were exposed to each of the three conditions for 20 minutes, and trials were separated by at least 24 hours to limit any habituation to the stimulus. To avoid possible circadian rhythm effects, each trial took place at the same time of day. A repeated measures design was used, and to minimise order effects the sequence in which the three conditions were presented was balanced using a Latin square design. Prior to the first session, participants received written and verbal instructions. The phenomenon of vection was explained to them while they were watching an upward translating random checker optic flow pattern. To ensure they differentiated between object- and self-motion, they watched the pattern until they reported a compelling sensation of vertical linear self-motion. This typically occurred after about 15 seconds. When they indicated that they fully understood the task, the experiment commenced.

Motion sickness measures

Motion sickness symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). Each participant completed the SSQ both before and after each session. Measures of interest were the change (post – pre exposure score) in the SSQ total scores and the SSQ subscores nausea, oculomotor, and disorientation.

Participants rated the severity of their motion sickness every minute on Bagshaw and Stott's (1985) sickness scale (1 no symptoms; 2 mild symptoms, but no nausea; 3 mild nausea; 4 moderate nausea). The experiment was stopped at malaise rating 4 or after 20 minutes, whichever was the sooner. Participants who reached a malaise rating of 4, and stopped, before 20 minutes

were assigned continuation values of 4. All the participants were initially symptom-free and the measures of interest were (i) the time for participants to first report a sickness rating of 2 (S2), (ii) the time to first report a rating of 3 (S3), (iii) the maximum sickness rating, (iv) the sum of the sickness ratings over the 20 min exposure duration ('accumulated sickness rating'). If no symptoms were reported, an accumulated sickness rating and symptom onset time of 21 were recorded.

Vection measures

To evaluate the time course and total duration of vection, participants were instructed to press a button whenever they experienced vection, and to keep it depressed for as long as they experienced it. The overall vection magnitude was assessed post exposure by asking participants to rate their experience in terms of the following question: 'Whilst watching the moving images, did you get the feeling of motion? Did you experience a compelling sensation of self-motion as though you were actually moving?' The endpoints of the 7-point Likert scale were anchored as 'not at all' (1) and 'very much so' (7). In conditions FB and RFB, as well as making this overall (o) rating, participants additionally evaluated vection magnitude in the individual directions that constituted the optic flow pattern: forward (F), backward (B) and roll (R).

Statistical analysis

Data analysis was performed using the software package SPSS (version 13). An initial analysis of the data revealed that no significant order effect was present (Appendix 27). For parametric and non-parametric dependent variables, data were compared using Tukey's HSD tests and Wilcoxon Signed Ranks tests, respectively. Correlations between different groups of measurements were assessed by Spearman's rho. Significance level was set to 0.05 for all tests.

6.4 Results

Sickness ratings

Table 6.1 shows the number of participants reaching each sickness rating before the 20 min maximum time cut-off. The time course of mean sickness ratings and the proportion of participants reporting vection are both shown in figure 6.1. (Individual data for each condition are presented in appendices 17-19). Whereas in conditions R and FB the mean sickness ratings (top) steadily increased over time, an unusual drop in mean sickness rating was observed in condition RFB. Inspection of individual data showed this trend to be consistent across participants.

TABLE 6.1 NUMBER OF PARTICIPANTS REACHING EACH SICKNESS RATING BEFORE MAXIMUM 20-MIN CUT-OFF.

	Condition		
Sickness rating	R	FB	RFB
2	9/12	8/12	8/12
3	5/12	5/12	5/12
4	3/12	4/12	3/12

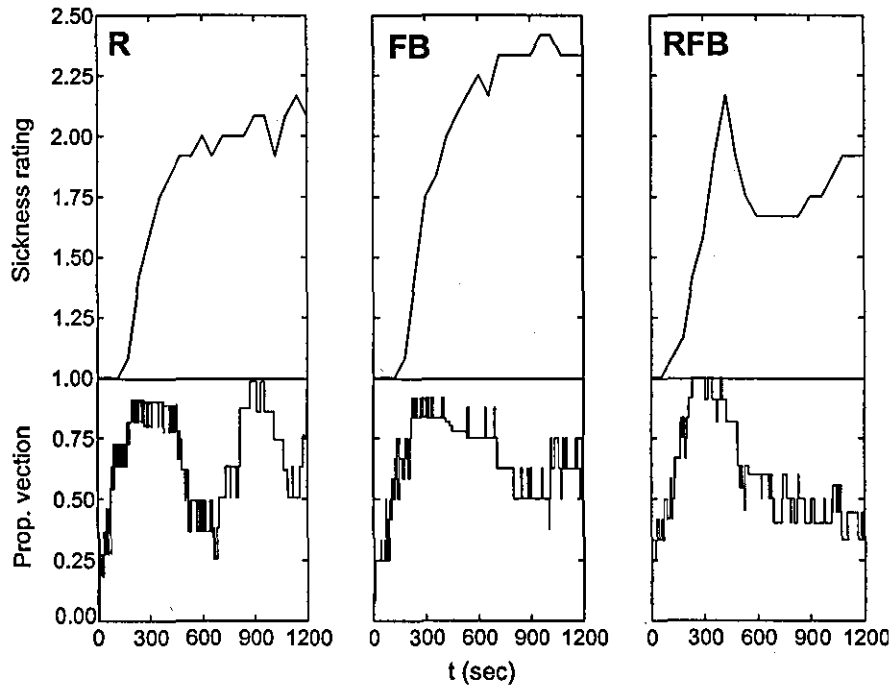


Fig 6.1 Mean sickness ratings (top) and proportion of participants reporting vection (bottom) as a function of time for each of the three conditions (Roll (R), Forward-Backward (FB), Roll + Forward-Backward (RFB)).

Figure 6.2a shows the mean accumulated sickness rating for each condition. The accumulated sickness rating in condition RFB was slightly lower than in conditions R and FB. None of the difference was statistically significant however.

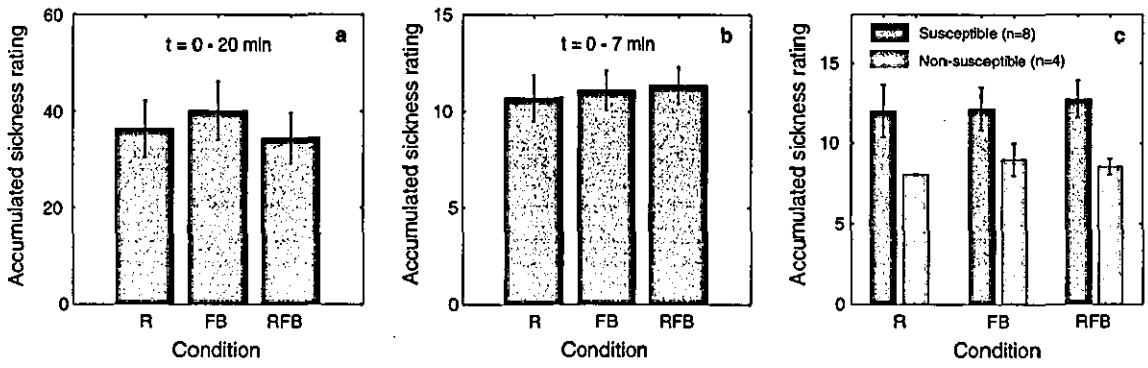


Fig 6.2 (a) Mean (± SEM) accumulated sickness rating for each condition over the complete trials (t = 0 – 20 min). (b) Mean (± SEM) accumulated sickness ratings for t = 0- 7 min. (c) Mean (± SEM) accumulated sickness ratings for t = 0- 7 min as a function of susceptibility.

To investigate whether the failure to find an effect of the experimental manipulation can be explained by the adaptation that evidently occurred in condition RFB (see figure 6.1), the first 420 seconds of the accumulated sickness ratings were analysed further. The results of the reanalysis are shown in figure 6.2b and it can be seen that the accumulated sickness rating was only slightly higher in condition RFB compared with the other conditions. None of the differences was significant.

To examine the possibility that the effect of the experimental manipulation was masked by differences in susceptibility between participants, a third analysis was performed in which participants were separated into a susceptible and a non-susceptible group. The susceptible group consisted of the eight participants who reported a sickness rating of 3 (mild nausea) during at least one of the three conditions. The remaining four participants formed the non- susceptible group. The accumulated sickness ratings based on the first 420 seconds (before any adaptation was seen) as a function of susceptibility are shown in

figure 6.2c. In the susceptible group, the accumulated sickness rating in condition RFB was slightly higher compared with conditions R and FB. However, the effect was small and failed to reach the required significance level.

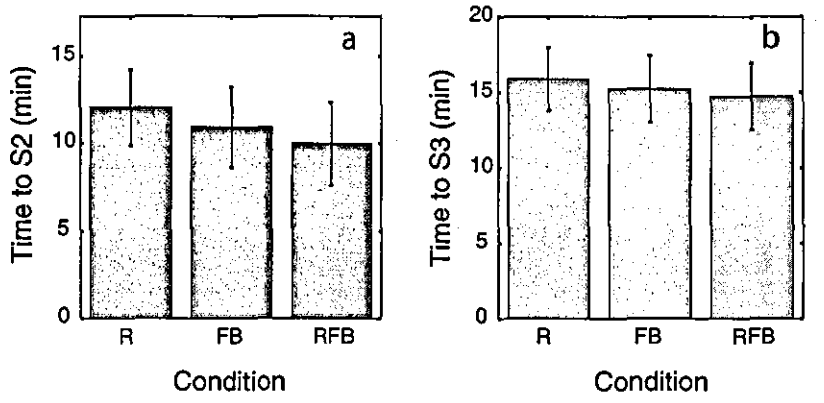


Fig 6.3 (a) Mean (± SEM) time to sickness rating 2 (S2). (b) Mean (± SEM) time to sickness rating 3 (S3).

Time to sickness ratings 2 and 3 are shown in figure 5.3a and b, respectively, for all twelve participants. Differences in time to sickness rating 2 and 3 between conditions were small and none were found to be significant.

Simulator Sickness Questionnaire (SSQ)

Figure 6.4 shows the SSQ total scores and the SSQ subscores N, O, and D for each condition. No significant differences were found in either the SSQ total scores nor the SSQ subscores.

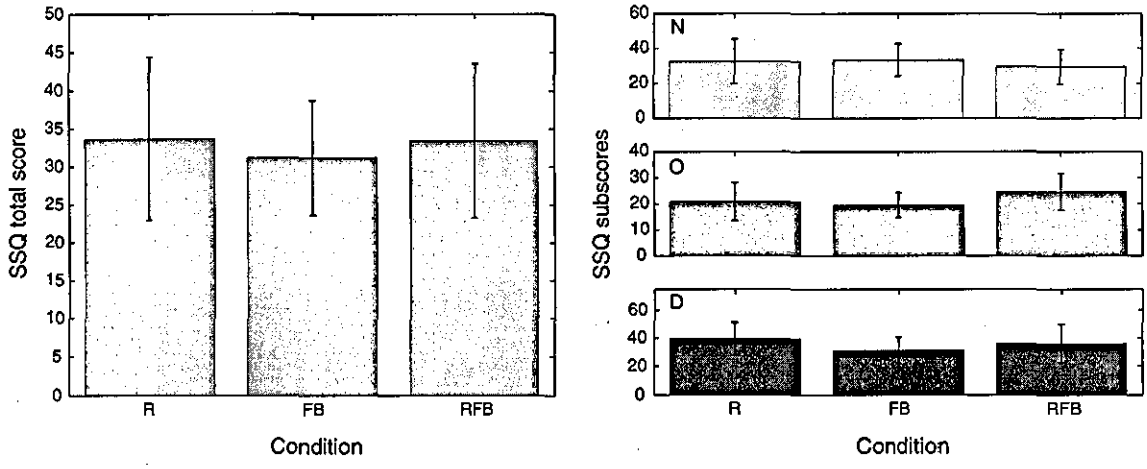


Fig 6.4 Mean (± SEM) SSQ total scores and SSQ nausea (N), oculomotor (O), and disorientation (D) subscores for each condition.

The mean changes (post - pre score) in symptom severity of the individual SSQ symptoms, are displayed in Figure 6.5. The largest changes were observed for the symptoms general discomfort, eyestrain, nausea, dizziness with eyes open, and stomach awareness.

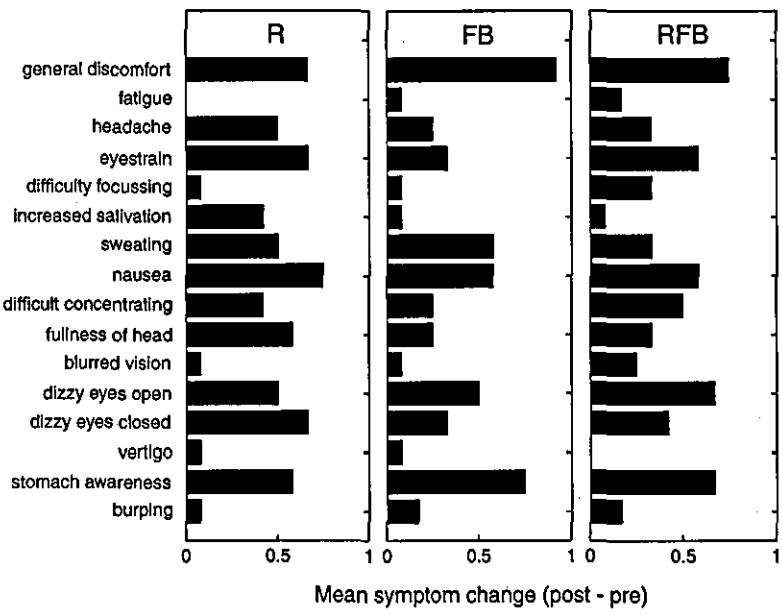


Fig 6.5 Mean change (post – pre score) in symptom severity of individual symptoms for the four conditions.

Vection

With the exception of one participant in condition FB, vection was reported by all participants in all three conditions. In condition RFB, participants perceived both translational and rotational vection simultaneously in directions opposite to those of the corresponding flow components. Anecdotal reports of participants following the dual-axis condition included descriptions of a corkscrew-like feeling of self-motion.

Figure 6.6 shows the mean vection magnitude ratings for each condition overall ('**condition**' *o*) and for each of the individual directions separately (R = roll, F = forward, B = backward). The overall magnitude was highest in condition R, followed by condition FB and RFB. Wilcoxon Signed Ranks tests demonstrated the overall vection magnitude in condition R to be significantly higher than in condition RFB ($p < 0.05$). This was consistent with participants' report that in condition RFB vection was mainly perceived in the anterior-posterior axis (i.e., forward – backward self-motion). Finally, backward vection was rated lower in condition RFB compared with condition FB, although this difference was not significant.

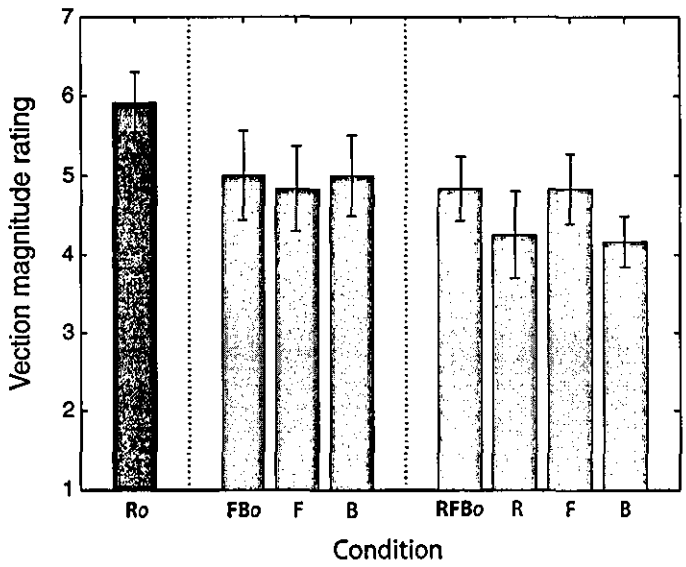


Fig 6.6 Mean (± SEM) vection magnitude ratings (1-7) for each condition overall (Ro, FBo, RFBo) and individual directions (R = Roll; F = Forward; B = Backward).

Figure 6.7a shows the mean percentage of the total exposure duration that vection was reported. Although non-significant, the percentage of time vection was reported tended to be shorter in condition RFB. Vection onset times are displayed in figure 6.7b. The data was abnormally distributed and hence, non-parametric tests were used which subsequently revealed no significant differences in vection onset times.

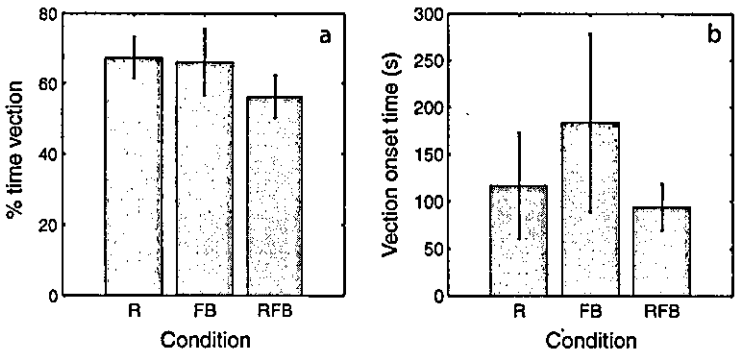


Fig 6.7 (a) Mean (± SEM) percentage of exposure duration vection was reported (%). (b) Mean (± SEM) vection onset time (sec) for each condition.

Table 6.3 shows the correlations (Spearman's rho) between the maximum sickness ratings and vection magnitude, duration, and onset times for each of the three conditions individually and pooled over conditions. The largest correlation coefficients were observed between maximum sickness ratings and vection magnitude.

TABLE 6.3 SPEARMAN CORRELATION COEFFICIENTS FOR MAXIMUM SICKNESS RATING AND VECTION MAGNITUDE, DURATION, AND ONSET FOR EACH CONDITION INDIVIDUALLY AND POOLED.

Condition	Vection magnitude	Vection duration (%)	Vection onset (sec)
R	$r_s = .539$	$r_s = .206$	$r_s = -.011$
FB	$r_s = .403$	$r_s = -.029$	$r_s = .124$
RFB	$r_s = .591^*$	$r_s = -.025$	$r_s = .188$
Pooled	$r_s = .702^*$	$r_s = -.179$	$r_s = .164$

* Significant at the 5% level

5.6 Discussion

The purpose of this study was to investigate whether dual-axis motion would elicit more VIMS than single-axis motion. Remarkably, exposure to dual-axis motion (i.e. combined rotational and translational motion) did not increase the level of motion sickness compared to exposure to its constituent parts in isolation despite the apparent additional sensory conflict. These results are difficult to explain in terms of a monotonic-additive model in which motion sickness is considered to be proportional to the degree of conflict (e.g., Oman, 1982, 1991; Reason, 1978) and suggest rotational and translational motion to be combined in a non-linear fashion.

Initially sickness ratings in all conditions gradually increased over time by similar amounts. However, in condition RFB, an atypical decrease in mean sickness ratings was then observed. Although it is a well known fact that habituation occurs after repeated exposure to a nauseating visual stimulus (e.g. Hettinger & Riccio, 1992; Hill & Howarth, 2000; Hodder & Howarth, 2003; Kennedy et al., 2000), and that during trials individuals will, on occasion, report decreases in symptom magnitude as well as increases, this *mean* decrease is a novel finding. This finding is also of importance from a methodological perspective for two reasons. First, it illustrates the importance of assessing the time-course of motion sickness in addition to pre- and post-exposure assessment. Secondly, the use of repetitive and unchanging optic flow patterns may lead to conservative estimates of the level of motion sickness when the effect of habituation is not accounted for in the analysis.

A clue to an explanation for the unexpectedly low level of VIMS during dual-axis motion is found in the observation that the overall vection magnitude tended to be lower during dual-axis motion than during single-axis motion patterns. Andre et al. (1996) observed a similar effect in that vection was experienced as less compelling when observers were exposed to the more complex pattern in which the stripes were tilted. If the degree of VIMS is a consequence of vection magnitude, then if the combined stimulus RFB does not produce vection which is equivalent to the addition of the components FB and R, one would not expect an equivalent increase in VIMS.

The present results indicated that roll and backward vection in particular, were experienced as less compelling during dual-axis motion in comparison with the two single-axis conditions. This would suggest that during compound self-motion perception, the constituent components are not independently processed, and may in fact mutually suppress each other (i.e., interaction effect).

In this context, it is of interest to refer to a study by Freeman and Harris (1992) in which the *detection* of expansion was found to be unaffected by the presence of rotation, and vice versa. Taken together with the existence of expansion- and rotation-selective neurons in area MST (e.g., Bruce et al., 1981; Sakata et al., 1985; Tanaka et al., 1989; Tanaka & Saito, 1989), the visual system thus appears to contain mechanisms selective for expanding or rotational retinal flow that function independently of each other in the analysis of complex retinal flow. The occurrence of "mutual suppression" in the current study suggests that at least with regard to *vection*, different mechanisms may be engaged that are not independent of each other.

Further support for this notion comes from the observation that compound vection (i.e., simultaneous rotational and translational vection) occurs when two flow vectors are summed, but not when two flow vectors are simply overlaid at the same depth plane (Ito & Fujimoto, 2003). When vertical and circular flows were overlaid, perceptual bistability occurred and only one flow induced vection at a given time. As pointed out by Ito and Fujimoto, if both flow vectors would be processed in parallel, a similar compound vection would have been expected to occur in the overlay condition.

An additional consideration is the possible role of attention. Attentional modulation of vection has been strikingly demonstrated in a study by Kitazaki and Sato (2003) in which observers were exposed to upward and downward moving dots of different colour (i.e., green and red) projected at the same depth plane. Dots moving in the same direction had the same colour, and observers were asked to attend to one of the two colours. Surprisingly, vection was perceived in the direction opposite to that of the non-attended motion. Since vection is known to be dictated by the background (e.g., Howard & Heckmann,

1989), a possible explanation for Kitazaki and Sato's findings is that the attended dots were perceived as foreground, whereas the non-attended dots were perceived as background. Although in the current study participants did not receive any attentional instructions, and furthermore, the optic flow pattern did not give rise to any foreground-background segregation, attention to either the rotational or translational motion component in the dual-axis motion pattern may have instigated vection to be dominated by the unattended motion component.

During exposure to dual-axis motion, both translational and rotational vection was experienced simultaneously in directions opposite to those of the corresponding flow components. This is consistent with earlier findings by Ito and Fujimoto (2003). Unlike Ito and Fujimoto's findings, however, vection duration was shortened during dual-axis motion compared with the single-axis motion patterns. This apparent discrepancy can be explained by the difference in exposure duration between their study (120 seconds) and ours (1200 seconds) because the decrease in the proportion of our participants reporting vection occurred after about 420 seconds.

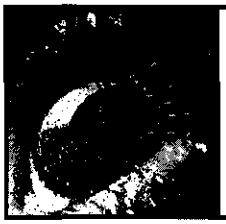
Adaptation has previously been shown to occur during prolonged stimulation for both linear (Berthoz et al., 1975) and circular vection (Brandt et al., 1974) as manifested by a steady decrease in vection velocity. However, the present results also indicate that the rate of adaptation may not be homogeneous across axes as the adaptation rate tended to be lower during linear motion, which, from an ecological perspective, may not be surprising.

The temporal correspondence between the time course of vection and sickness rating, as well as the strong correlations between vection magnitude and motion sickness, suggest a causal relationship between vection and motion sickness. However, a similar decrease in vection was observed in condition R without a concomitant decrease in mean sickness rating. Inspection of the individual trial records (appendices I-III) shows that i) the onset of symptoms is always preceded by the occurrence of vection, but may linger on after vection has dissipated, and ii) participants who do not experience motion sickness may nevertheless experience compelling sensations of vection. Vection therefore

appears to be a necessary precursor of VIMS (see also Hettinger & Riccio, 1992), whereas individual differences in sensitivity to sensory conflict may determine whether or not motion sickness occurs.

6.6 Conclusion

Dual-axis motion did not increase the level of motion sickness compared with single-axis motion, despite apparent additional sensory conflict. This finding is inconsistent with VIMS being determined by simple summation of the provocative stimuli, and suggests that rotational and translational motion stimuli are not independently processed.



C_7
Predictability of VIMS

7.1 Summary

This chapter investigates the correlations between VIMS and past history of motion sickness as assessed by the revised Motion Sickness Susceptibility Questionnaire (MSSQ). Whereas the predictive validity of the revised MSSQ has previously been evaluated with respect to true motion sickness and other non-motion emetogenic stimuli such as chemotherapy, the validity with respect to VIMS is unknown. The analysis was based on the data obtained from the studies described in chapters three to six (n = 60). Obtained correlation coefficients between the revised MSSQ and SSQ total scores and maximum sickness ratings were r = 0.51 and r = 0.37, respectively. These values are similar to those reported regarding true motion sickness and are suggestive of a common underlying pathway. In terms of predicting individual behaviour, the use of the revised MSSQ may however be limited in that the MSSQ failed to identify 50% of those individuals who requested termination of the experiment prematurely due to symptom severity. Finally, the revised MSSQ may be in need of cultural validation rather than mere translation when used with non-Caucasian populations.

7.2 Introduction

Within VR systems, the percentage of individuals reporting side effects has been estimated to be around 80 to 95% and whereas for the majority these effects are mild and quickly subside, around 5 to 30% experience symptoms severe enough to discontinue exposure (Cobb et al., 1999; Kennedy & Stanney, 1997; Wilson et al., 1997). In simulators, the prevalence of side effects reported tends to be slightly lower and has been estimated to be around 60 to 70% (Stanney et al., 1999), where 5% of users have been estimated to experience severe symptoms (Kennedy, 1996).

In the current studies, the symptoms have all been produced by a purely visual stimulus. Comparing the frequency of occurrence of side effects in the current sample (chapters 3-6) to these estimates, the figures fall within the higher range: 88% of the participants reported mild symptoms (e.g., eyestrain, dizziness, headache, and stomach awareness), 38% reported mild nausea, whereas 23% reported moderate nausea and had to discontinue the experiment before the maximum time cut-off (see Table 7.1)[1]. These data also exemplify the large inter-individual variability in susceptibility, which has been associated with factors such as age, gender, ethnicity, perceptual style, and experience (for a review see Kolasinski, 1995).

In the context of managing VIMS, the ability to predict the likelihood and the extent to which an individual will develop adverse side effects is of relevance for a number of reasons. As pointed out by Kennedy et al. (2001), i) susceptible individuals may be exposed to special habituation programs ahead of time, ii) it may be necessary to design special VR interfaces to reduce the prevalence of

[1] It should be noted that in studies such as reported here, the percentages are likely to be conservative estimates for methodological-ethical reasons. First, volunteers must be informed that the experiment may cause nausea and motion sickness. Consequently, individuals who know themselves to be susceptible to motion sickness may often decline. This self-selective procedure creates a bias within a participant group and might significantly reduce the proportion of individuals suffering from motion sickness. This problem has particularly been acknowledged with regard to military participants (Lawson et al., 2002; Regan & Price, 1994). Secondly, the use of repeated measures designs will dampen the overall symptom severity due to habituation to the provocative stimulus (e.g., Hodder & Howarth, 2003; Howarth & Blackmore, 2002).

adverse side effects, and iii) exclusion of highly susceptible individuals reduces the risk of compromising experimental studies of VR as a system interface due to participant drop-out.

TABLE 7.1 NUMBER OF PARTICIPANTS REACHING EACH SICKNESS RATING FOR EACH OF THE EXPERIMENTS AND IN TOTAL

			Sickness rating		
Experiment	n	Motion stimulus	S2	S3	S4
(a) Chapter 3	12	Horizontal translational oscillation x-axis 0.025 Hz; Roll motion 0.125Hz; Constant velocity	10	3	2
(b) Chapter 4.1	12	Horizontal translational oscillation x-axis 0.025 - 0.2 Hz	9	3	2
(c) Chapter 4.2	12	Horizontal translational oscillation x-axis 0.2 – 1.6 Hz	11	4	2
(d) Chapter 5	12	Horizontal translational oscillation x-axis 0.2 Hz; Roll motion 0.2 Hz; Spiral motion	11	8	5
(e) Chapter 6	12	Horizontal translational oscillation x-axis 0.2 Hz; Changing gaze position	12	5	3
Total	60		53 (88%)	23 (38%)	14 (23%)

S2, S3, S4: sickness rating 2 (mild symptoms, but no nausea), 3 (mild nausea), and 4 (moderate nausea), respectively.

Kennedy and colleagues (1990) conducted a meta-analysis of the predictive validity of several predictors of susceptibility to various forms of motion sickness including VIMS and concluded that highest predictive validities were obtained with operational measures, followed by laboratory simulations (provocative tests), motion sickness history, psychological factors (personality and perceptual style), and physiological measures (autonomic and sensory function).

Despite their superior predictive validity, operational measures and laboratory simulations are of limited practical value. The main disadvantages are their provocative nature and the obvious logistical issues. In the light of cost-effectiveness, convenience to the individual, and high measurement reliability (± r = 0.80 (Kennedy et al., 1990)), assessment of an individual's motion sickness history may thus provide a useful and practical method for predicting motion sickness.

Over the last decades, a number of questionnaires have been developed to assess an individual's motion sickness history. These questionnaires share common elements indicating the types of motion or vehicles that have made the individual sick, the frequency of sickness, and the severity of symptoms. The most widely used and validated questionnaires are the Pensacola Motion History Questionnaire (MHQ) (Kennedy & Graybiel, 1965) and the Motion Sickness Susceptibility Questionnaire (MSSQ) (Reason, 1968). Both questionnaires have been shown to predict the frequency and the severity of motion sickness symptoms over a wide range of provocative conditions, including air and sea exposure, vertical acceleration, cross-coupled Coriolis stimulation, and simulator training (Kennedy et al., 1990; Reason & Brand, 1975). The finding that individuals who report decreased tolerance to some forms of motion show increased sensitivity to other forms of unusual motion conditions suggests a common physiological basis in the development of motion sickness (Golding, 1998; Hu et al., 1996).

Whereas the MSSQ has remained unchanged until recently (Golding, 1998), the MHQ has undergone numerous modifications over the years, including adjustments of scoring keys for specific motion environments (Kennedy et al., 1990). Most recently, Kennedy et al. (2001) developed and validated updated scoring keys for the MHQ and reported correlation coefficients of $r = .41$ and $r = .45$ against a criterion of VIMS obtained after exposure to a helmet-mounted VR display ($n = 766$).

Positive correlations have also been found between motion sickness history as assessed by Reason's MSSQ and VIMS. In an optokinetic drum study, Hu et al. (1996) reported a correlation of $r = .54$ ($n = 49$) between the MSSQ scores and total sickness scores based on Graybiel et al.'s (1968) motion sickness scale.

The MSSQ has however often been criticised for its difficulty to complete without guidance or explanation (e.g., Golding, 1998; Nichols, 1999). Noting that when respondents have difficulty with a questionnaire, the chance of errors and non-responses is considerably increased, Golding (1998) revised the original MSSQ with regard to its format and scoring method. The predictive validity of the revised MSSQ, which was shown to correlate well ($r = .99$) with

the more complicated original MSSQ, was evaluated based on data obtained in a number of laboratory studies in which individuals were exposed to physically moving environments, i.e., cross-coupled Coriolis stimulation and oscillating vertical and horizontal translation. Correlations obtained with the revised MSSQ using the simplified scoring method averaged at r = .45 across the different studies (Golding, 1998).

More recently, Bos et al. (2005) reported a correlation of r = .60 (n = 24) between the revised MSSQ and motion sickness induced by multi-axis motion stimulation in a ship motion simulator, whereas a correlation of r = .36 (n = 309) was reported in a study using cross-coupled Coriolis as the provocative stimulus (Klosterhalfen et al., 2005).

Since the revised MSSQ was filled out by all participants in the studies reported in this thesis, the aim of this chapter was to evaluate the predictive validity of the revised MSSQ with respect to VIMS.

7.3 Methods

Participants

In total 60 (43 males, 17 females) participants were recruited amongst the student and staff population of Loughborough University and Waseda University, Japan. The age range of participants was 20 to 40 years (mean = 26.32, SD = 5.30). The participants who were recruited at Waseda University were of Asian origin. Participants were otherwise predominantly of Caucasian origin. The experimental protocol was approved by the Loughborough University and Waseda University Ethical Advisory Committee, and participants gave their informed consent to participate in the study. All had intact vestibular function, none were receiving any medication, and all had normal or corrected-to-normal vision.

Apparatus and stimuli

The experiments entailed exposure to random dot optic flow patterns simulating a variety of motion patterns, including translational motion in the anterior-posterior axis, roll motion, and spiral motion. The visual stimuli were presented on a rear projection TV (chapter 6) or backprojected onto a tangent screen covering approximately 65° (h) x 59° (v) of the visual field (chapters 3 to 5).

Procedure

A common procedure was used in all of the experiments. Except for the study described in chapter 6 in which the exposure duration was set at 10 minutes, participants were exposed to the visual stimulus for a maximum of 20 minutes. To limit any habituation to the stimulus, each session was separated by at least 24 hours. In addition, sessions took place at the same time of day in order to avoid possible circadian rhythm effects. A repeated measures design was used with each participant acting as his/her own control. To minimise order effects, in each experiment the order in which conditions were presented was balanced using a Latin square design. Prior to the first session, participants received written and verbal instructions and completed the MSSQ.

Motion sickness measures

Motion sickness symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). Each participant completed the SSQ both before and after each session. The measure of interest was the change (post – pre exposure score) in the SSQ total scores.

In addition, participants rated the severity of their motion sickness at one-minute intervals on Bagshaw and Stott's (1985) sickness scale (1 no symptoms; 2 mild symptoms, but no nausea; 3 mild nausea; 4 moderate nausea). The experiment was stopped at malaise rating 4 or after the maximum exposure duration (i.e., 10 or 20 min), whichever was the sooner. The measure of interest was the maximum sickness rating achieved during exposure.

Revised Motion Sickness Susceptibility Questionnaire (MSSQ)

The MSSQ is a two-section questionnaire used for the assessment of motion sickness history (Golding, 1998). The questionnaire asks for previous sickness occurrences in cars, busses, trains, aircraft, small boats, large ships, swings, merry-go rounds, and leisure park attractions for ages up to 12 (MSSQ-A), as well as for the past 12 years (MSSQ-B). The occurrence of nausea and vomiting, corrected for reported travel experience, are used to establish an index of susceptibility. This results in a single MSSQ raw score (MSSQ-AB) ranging from 0 to 190, with the 50th percentile of a normal population reached at MSSQ 37. In addition, the MSSQ includes a single-item susceptibility question which reads as follows: "Do you regard yourself susceptible to motion sickness?"; answer categories: "Not at all", "Slightly", "Moderately", and "Very much so".

Validity analysis

The participants' motion sickness history derived from the MSSQ was scored using the method provided by Golding (1998) (see appendix X for details). To evaluate the predictive validity of the MSSQ, the SSQ total scores and maximum sickness ratings for each participant were averaged over conditions and subsequently correlated with the individual MSSQ-A, MSSQ-B, and MSSQ-AB (raw) scores for each study separately. Correlations were assessed by Pearson's r.

7.4 Results

Single-Item Motion Sickness Susceptibility

The majority of responses were in the "not at all" (30.0%) and "slightly" (43.3%) categories; 23.3% were in the "moderately" category, whereas 3.3% were in the "very much so" category. The correlation between the single item and the MSSQ-AB score was $r_p = 0.57$ ($p < 0.001$).

Norms

The MSSQ-AB scores were positively skewed with a mean of 40.0 (SD = 30.6) The mean percentile score for the participants in this study was 50% which indicates the sample to be equally susceptible to motion sickness as the normal population (Golding, 1998). The mean subscores were significantly higher for part A (childhood), 22.1 (SD = 19.0) than part B (adult life), 16.3 (SD = 14.5) ($p = 0.005$, t-test). The female mean MSSQ-AB score, 45.35 (SD = 44.14), was not significantly higher than the male mean MSSQ-AB score, 37.94 (SD = 23.66) ($p = 0.403$, t-test).

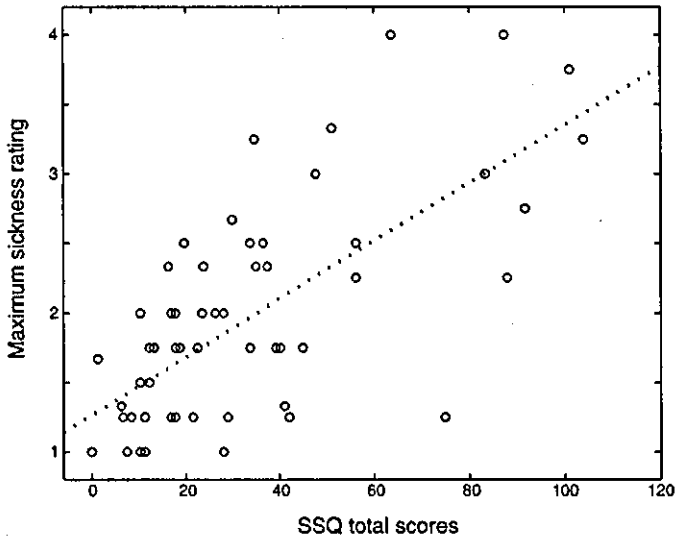


Fig 7.1 Maximum sickness ratings plotted versus the Simulator Sickness Questionnaire (SSQ) scores for all experiments. The dotted line gives the best linear fit (y= 0.021*x + 1.3).

Relationship between motion sickness measures

The scatter plot of the SSQ total scores versus the maximum sickness ratings averaged across conditions indicated the expected positive relationship (figure 7.1). The correlation analysis showed a significant correlation between the SSQ total scores and the maximum sickness ratings ($r_p = 0.70$, $p < 0.001$).

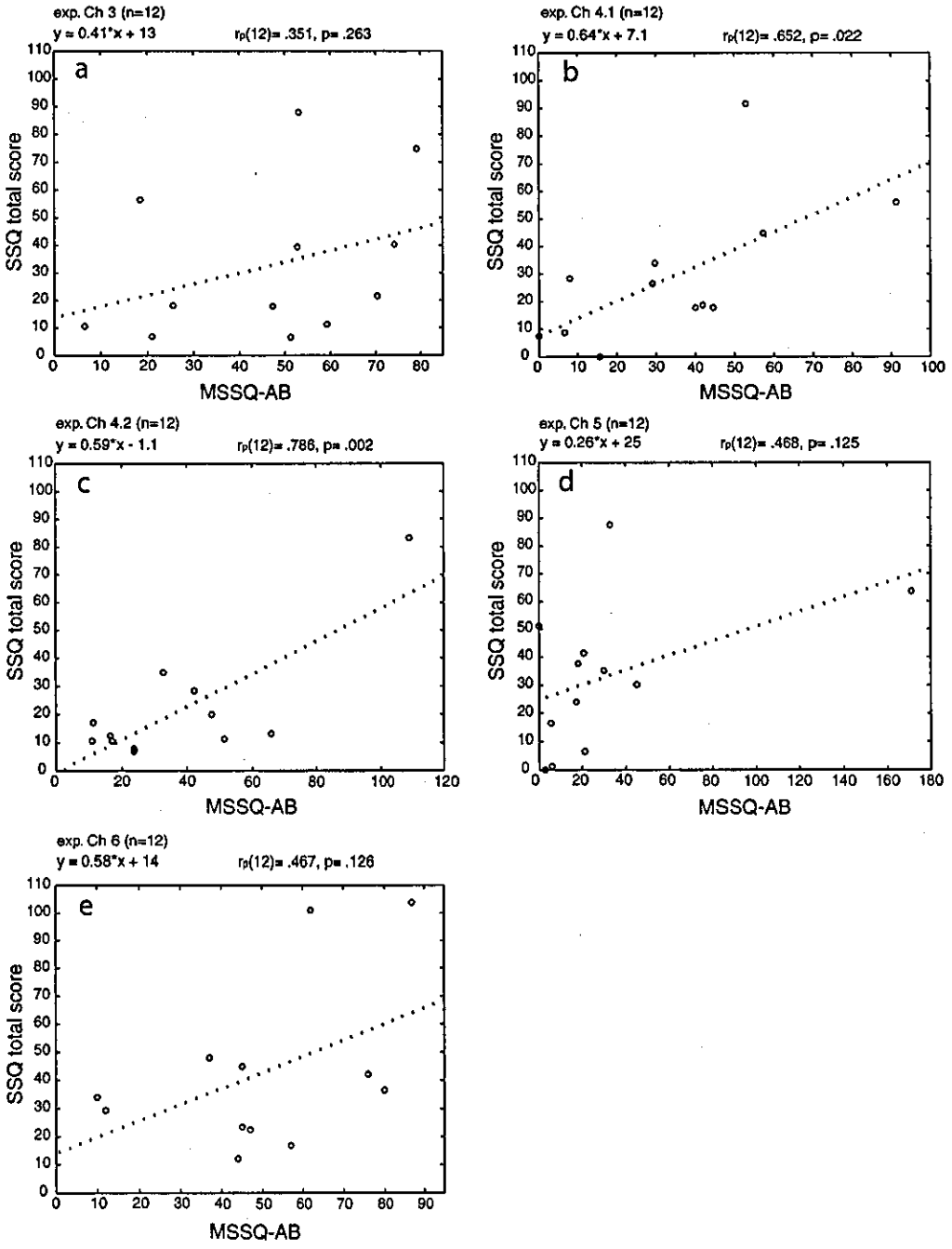


Fig 7.2 Simulator Sickness Questionnaire (SSQ) total scores plotted versus the motion sickness susceptibility questionnaire raw scores (MSSQ-AB) for each experiment (a-e) (see also table 7.2). The dotted lines give the best linear fit. Regression equations, Pearson's r-values and significance levels are shown for each study individually.

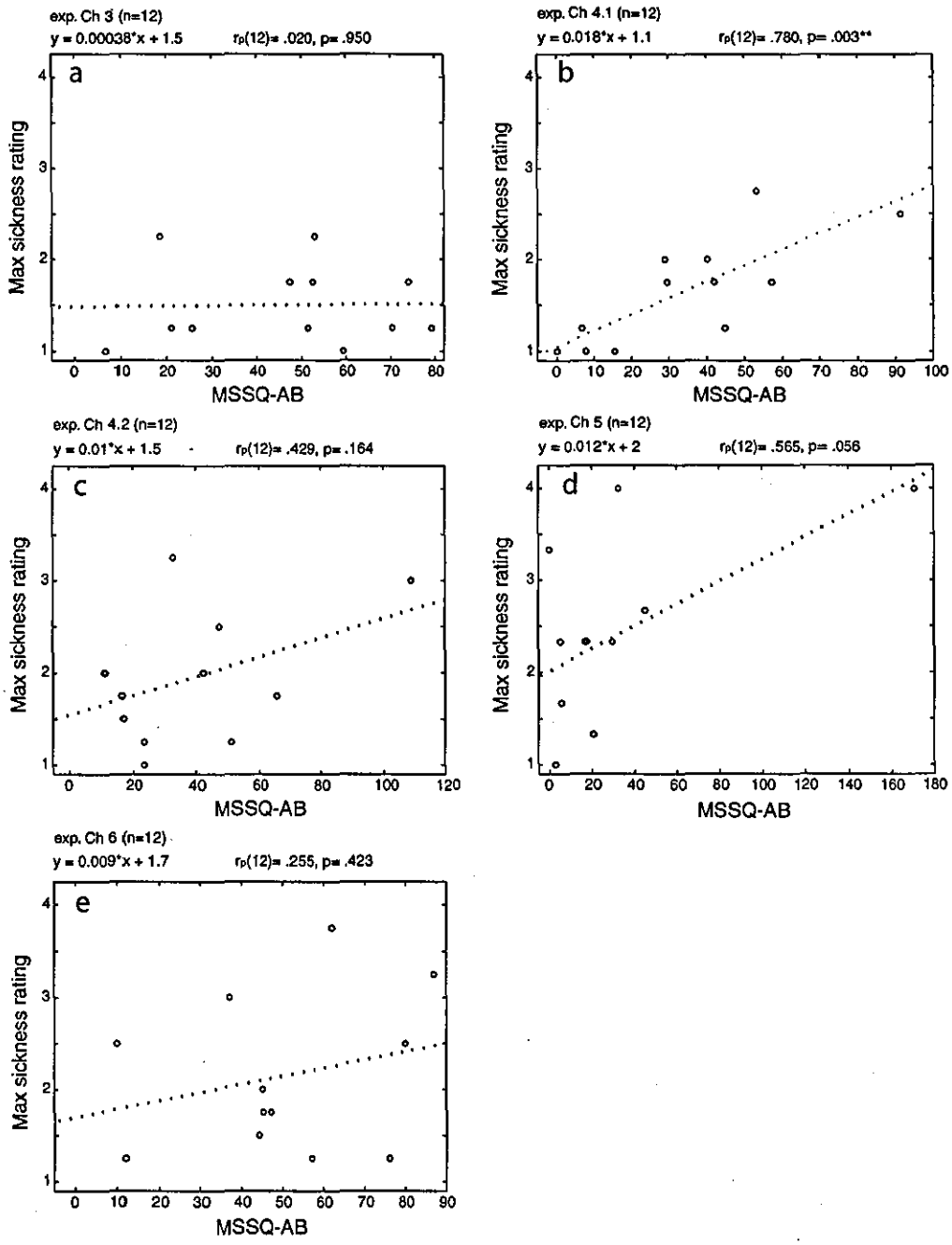


Fig 7.3 Maximum sickness ratings plotted versus the motion sickness susceptibility questionnaire raw scores (MSSQ-AB) for each experiment (a-e) (see also table 7.2). The dotted lines give the best linear fit. Regression equations, Pearson's r-values and significance levels are shown for each study individually.

MSSQ predictive validity

Figures 7.2 and 7.3 show the scatter plots of the SSQ total scores and maximum sickness ratings respectively versus the individual MSSQ-AB scores for each of the five studies (a-e, see Table 7.1). Overall, the scatter plots

indicated a positive relationship between the MSSQ-AB and motion sickness. Correlations between the MSSQ-A, MSSQ-B, MSSQ-AB and SSQ total scores and maximum sickness ratings are summarised in table 7.2. Pooled correlations of the MSSQ-AB with the SSQ total scores and maximum sickness ratings were $r_p = 0.51$ and $r_p = 0.37$, respectively.

TABLE 7.2 VALIDITY OF THE REVISED MSSQ IN PREDICTING VIMS (PEARSON'S R)

Experiment	n	Age mean *(SD)*	MSSQ mean *(SD)*	MSSQ-A x SSQ	MSSQ-B x SSQ	MSSQ-AB x SSQ	MSSQ-A x Max	MSSQ-B x Max	MSSQ-AB x Max
(a) Ch. 3	12	28.6 *(5.7)*	55.3 *(25.4)*	0.17	0.40	0.35	0.10	-0.09	0.02
(b) Ch. 4.1	12	29.8 *(5.8)*	44.0 *(27.6)*	0.55	0.64*	0.65*	0.64*	0.82**	0.78**
(c) Ch. 4.2	12	24.6 *(2.8)*	44.4 *(25.1)*	0.85**	0.48	0.79**	0.49	0.22	0.43
(d) Ch. 5	12	26.1 *(6.1)*	29.3 *(27.1)*	0.54	0.35	0.47†	0.60*	0.49	0.57†
(e) Ch. 6	12	22.6 *(1.3)*	50.2 *(24.2)*	0.09	0.68*	0.47	0.07	0.35	0.26
Pooled	60	26.3 *(5.3)*	40.0 *(30.6)*	0.42**	0.47**	0.51**	0.34**	0.30*	0.37**

*,** Correlation is significant at the 0.05 and 0.01 level respectively (2-tailed).
† The correlations were heavily influenced by one participant in particular who was highly susceptible but reported a low MSSQ score (see panel d of figure 7.2 and 7.3). With the participant excluded from the analysis, correlation coefficients rose to r = .610 (SSQ) and r = .650 (Max sick rating), both significant at the 0.05 level.

Extreme groups

As mentioned in the introduction, the ability to identify highly susceptible individuals may have some distinct benefits. A further analysis was therefore performed to see to what extent the revised MSSQ is able to differentiate susceptible form non-susceptible individuals. The 60 participants were divided into three equal sized groups based on their MSSQ-AB scores. These groups were defined as low, medium, or high susceptible.

The grouping resulted in the following distribution of participants: 20 participants in the low-MSSQ group (13 male, 7 female); 20 participants in the mid-MSSQ group (16 male, 4 female); 20 participants in the high-MSSQ group (14 male, 6 female). The means and standard deviations of MSSQ scores were 11.23 ±

6.70 for the low-MSSQ group, 36.41 ± 8.91 for the mid-MSSQ group, and 72.47 ± 28.23 for the high-MSSQ group.

TABLE 7.3 TOTAL SSQ SCORES AND MAXIMUM SICKNESS RATING FOR THE THREE MSSQ GROUPS

Measures	Group		
	Low MSSQ (n = 20)	Middle MSSQ (n = 20)	High MSSQ (n = 20)
SSQ total scores	19.98 ± 16.81	26.87 ± 18.36	48.16 ± 32.63
Max sickness rating	1.71 ± 0.66	2.01 ± 0.77	2.06 ± 0.90

Data presented as means ± SD

Table 7.3 presents the means and standard deviations of the total SSQ scores and maximum sickness ratings for the three groups. Tukey post-hoc tests indicated that the high-MSSQ group developed significantly higher total SSQ scores than the low- and mid-MSSQ group ($p < 0.05$). The total SSQ score in the middle-MSSQ group was higher than the low-MSSQ groups, but the difference was not statistically significant. The maximum sickness ratings followed the same pattern trend although the differences were not found to be statistically significant.

Table 7.4 shows the frequency of symptoms in each of the three MSSQ groups. For each individual study, the number of sessions on which a particular symptom was reported was calculated as a percentage of the total number of sessions (conditions) in the respective study. For example, if a participant reported stomach awareness during one of the four experimental conditions, a percentage value of 25 was assigned. Individual percentages for each of the symptoms were then averaged over the whole sample. It can be seen that the frequency of symptoms of motion sickness was the highest in the high-MSSQ group, followed by the middle-MSSQ group, and then the low-MSSQ group.

TABLE 7.4 FREQUENCY OF SYMPTOMS IN EACH OF THE THREE MSSQ GROUPS

	Groups			
Symptoms	Low-MSSQ	Mid-MSSQ	High-MSSQ	Total (n=60)
General Discomfort	40%	49%	55%	48%
Fatigue	29%	39%	36%	35%
Headache	18%	16%	36%	24%
Eyestrain	58%	46%	71%	58%
Difficulty focussing	14%	28%	60%	34%
Increased Salivation	3%	23%	28%	18%
Sweating	25%	27%	26%	26%
Nausea	19%	22%	38%	26%
Difficulty concentrating	16%	33%	50%	33%
Fullness of head	15%	26%	43%	28%
Blurred vision	10%	20%	40%	23%
Dizzy (eyes open)	19%	16%	33%	23%
Dizzy (eyes closed)	15%	15%	41%	24%
Vertigo	0%	6%	15%	7%
Stomach awareness	27%	28%	33%	29%
Burping	8%	25%	15%	16%

Whereas the MSSQ differentiated low- from highly- susceptible individuals based on the SSQ at the group level, inspection of individual data showed that the MSSQ identified only seven out of fourteen participants who requested termination of the experiment prematurely due to symptom severity. This is also illustrated in figure 7.4 in which the MSSQ raw scores are separately plotted for those participants who completed the trials (*ok*) and those who requested to terminate the experiment prematurely (*drop-out*). The dashed lines indicate the MSSQ scores at which the sample was divided into three groups of equal n. It can be seen that a more stringent criterion would have identified more participants who dropped out.

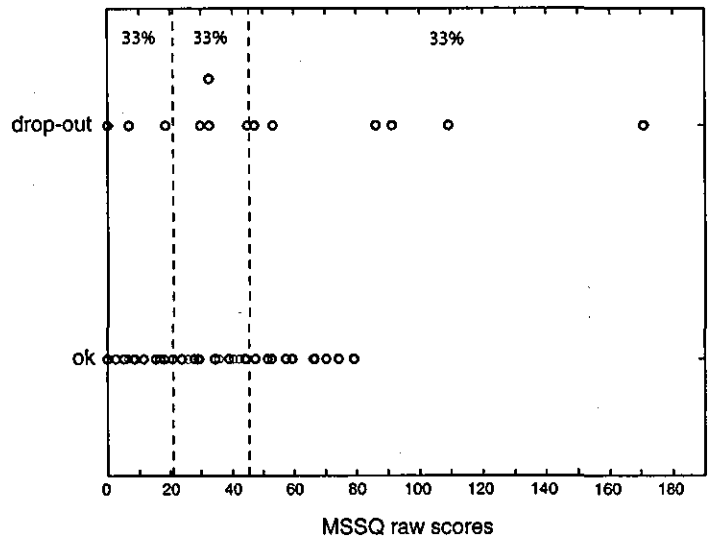


Fig 7.4 MSSQ raw scores plotted separately for participants who completed the trials (ok) and those who requested to terminate the trials before the cut-off point (drop-out).

7.5 Discussion

The main aim of this study was to evaluate the validity of the revised Motion Sickness Susceptibility Questionnaire (Golding, 1998) in predicting VIMS. Based on the studies described in the previous chapters, pooled correlations between MSSQ-AB scores and the SSQ and maximum motion sickness scores were r = 0.51 and r = 0.37, respectively. These results are consistent with the findings of previous studies that the past history of motion sickness can to some degree predict susceptibility to a variety of motion sickness-provoking situations, including both physically moving environments (Bos et al., 2005; Golding, 1998; Klosterhalfen et al., 2005) and optokinetic stimulation (Hu et al., 1996; Kennedy et al., 2001). Correlation coefficients in these previous studies also tended to be around r = 0.40 and r = 0.50, which suggests that approximately 20% of the variance in motion sickness may be accounted for by motion history. Furthermore, the finding that susceptibility to VIMS is correlated with susceptibility to true motion sickness as assessed by the revised MSSQ lends support to the contention of a common underlying mechanism (Golding, 1998; Hasegawa et al., 1992; Hu et al., 1996), although the possibility of mere association cannot be ruled out, i.e., those reporting a higher susceptibility to

other forms of motion sickness may also be more inclined to report higher levels of VIMS.

It should be noted that not all correlations presented in the current study reached the required significance level. However, as pointed out by Kennedy et al. (1990), the finding that obtained relationships are typically low and may fail to reach the required significance level is primarily due to sample size and measurement unreliability, and only at a secondary level can inadequate prediction be attributed to the underlying relations between predictors and criteria. The effect of measurement reliability on the predictive validity is expressed in the Cauchy-Schwarz Inequality which states that the upper limit for predictive validity is the geometric mean of the criterion reliability and the predictor reliability (Kendall & Stuart, 1977). This implies that both the predictor and criterion must be able to predict itself (measurement reliability) adequately for the predictor to successfully predict the criterion.

Measurement reliability and subsequent predictive validity is adversely affected by a number of factors (see Kennedy et al., 1990) including positive skew in the underlying distribution (Dunlap et al., 1994), a common finding in motion sickness studies (e.g., Golding, 1998) that was also observed in the current study (see figures 7.1-3). Range restriction or lack of variability in the criterion is a further factor that is likely to have deflated the correlations in the current study. As was shown in table 7.1, the large majority of participants reported only mild symptoms. The effect of range restriction was particularly apparent in the first study in which the stimuli were relatively benign (see figure 7.2a and 7.3a).

Finally, it is not clear to what extent the correlations in the study presented in chapter 6 were affected by the fact that the MSSQ has not been validated for non-Caucasian populations. This issue was also recently raised by Klosterhalfen et al. (2005) who had shown that MSSQ ratings may be differently affected by ethnicity. It was found that the MSSQ ratings given by Chinese volunteers did not reflect their higher susceptibility during subsequent cross-coupled Coriolis stimulation. The underlying reasons remained elusive but may be related to text-translational problems, awareness of susceptibility, differences in motion sickness history (i.e., Chinese may experience less

nausea evoking symptoms in their daily life), and cultural or social reasons (Klosterhalfen et al., 2005). It is of interest to note that in the process of translating the MSSQ into Japanese for the study presented in chapter 6, the question with regard to experience with (playground) roundabouts was considered irrelevant and initially omitted by one of the translators as roundabouts are virtually unknown in Japan. Whereas omission of or zero response to this particular item is not likely to significantly affect MSSQ scores, the example illustrates the necessity of cultural validation of questionnaires rather than mere translation. This is further exemplified by the observation that 50% of the participants in the study discussed in chapter 6 reported "mental depression" whereas none of the predominantly Caucasian participants in the remaining studies reported this item.

Overall, the correlational analysis showed that the more severe the motion sickness previously experienced in different motion modes, the more severe the VIMS. However, the observed correlations were rather low for the prediction of individual behaviours. In line with earlier findings (Golding, 1998; Klosterhalfen et al., 2005), some participants who reported no motion sickness in previous motion conditions according to the MSSQ nevertheless reported substantial levels of motion sickness (figure 7.2d and 7.3d). On the other hand, those participants reporting a history of severe motion sickness generally also reported the highest levels of VIMS. In other words, the MSSQ is better at resolving susceptibility differences at the non-resistant end of the continuum.

Contrary to previous findings by Klosterhalfen et al. (2005), the revised MSSQ was unable to unequivocally distinguish highly susceptible from non-susceptible individuals in the current sample. Although the SSQ total scores were significantly higher for the high-susceptible group, the MSSQ was not successful in categorizing susceptible individuals based on the mean maximum sickness ratings. Moreover, the MSSQ failed to identify 7 out of 14 participants who terminated the experiment prematurely due to symptom severity as highly susceptible. Adopting a more stringent criterion value for exclusion would have excluded more participants who failed to complete the trials. However, this comes at an expense as this unnecessarily excludes participants who would

have been able to complete the trial. Criterion setting thus becomes a question of available resources (i.e., availability of subject pool with low MSSQ scores) and research aims (e.g., motion sickness study vs. design evaluation).

7.6 Conclusions

The results of the current study indicate that the revised MSSQ can predict VIMS to a similar degree as it is able to predict true motion sickness which is suggestive of a common underlying mechanism between the different forms of motion sickness. As a screening tool, the revised MSSQ is limited in that it cannot distinguish among those who claim not to have experienced sickness even though differences in susceptibility exist within this group. Secondly, the MSSQ is unable to identify all highly susceptible individuals, i.e., those that request termination of the experiment due to symptom severity. Finally, the MSSQ may require cross-cultural validation for the use of non-Caucasian populations.

C_8
Summary and conclusions

8.1 Summary

This chapter summarises the main findings of the work presented in this thesis, discusses some limitations and suggestions for future research, and concludes with some final remarks.

Unlike research into other forms of motion sickness, such as seasickness, little research has been conducted investigating the elementary components thought to underlie the aetiology of VIMS, i.e. the visual stimulus characteristics. To date, despite the dominance of fore-and-aft motion in both real and simulated environments, VIMS has typically been studied using angular motion profiles. In contrast, the work presented in this thesis investigated the interrelationship between visual stimulus characteristics, VIMS, and vection during simulated self-motion in the fore-and-aft axis.

- In the first study, stationary observers were exposed to radial displays simulating either constant or sinusoidally oscillating velocity self-motion. The absence of the elevated level of VIMS expected to occur was hypothesised to be a consequence of the particular frequency employed.

- The frequency dependence of VIMS was subsequently tested. Within the range 0.025 - 1.6 Hz, VIMS was found to peak at 0.2 Hz. Studies employing angular motion stimulation had previously shown a peak in VIMS to occur at a frequency of approximately 0.06 Hz, which suggests that results obtained with angular motion stimulation cannot be extrapolated to scenes involving fore-and-aft motion stimulation.

- The studies presented thus far isolated the effect of stimulus characteristics by preventing eye movements from occurring by means of fixation. In contrast, the next study was conducted with the express

purpose of investigating the effect of gaze shifting. It was found that the level of VIMS significantly increased with fixation away from the focus of expansion of a radial optic flow suggesting that the visual stimulus interacts differently with different portions of the retina.

- Real-world motion scenarios generally entail motion along different axes simultaneously. The next study, described in chapter 6, compared VIMS during single- and dual-axis motion. Dual-axis motion did not exacerbate the level of VIMS challenging the generally held assumption that VIMS is proportional to the degree of conflict.

- The feasibility of predicting the incidence of VIMS based on individuals' motion sickness history as assessed by the revised Motion Sickness Susceptibility Questionnaire (MSSQ) was then explored. Correlation coefficients were comparable to those observed with true motion suggestive of a common underlying mechanism between different forms of motion sickness. For the prediction of individual behaviour, the MSSQ was found to be of limited value in its current form.

  An overall finding was that vection was found consistently to precede the occurrence of VIMS and strongly suggests vection to be a prerequisite for VIMS to occur. Significant positive correlations between vection magnitude and VIMS indicated that those individuals experiencing stronger feelings of vection were also likely to experience more VIMS.

8.2 Limitations and suggestions for future research

The work described in the current thesis has highlighted several findings that indicate that VIMS in response to linear motion in the fore-and-aft axis differs from that in response to angular motion (yaw, pitch, roll) typically employed in VIMS research. In particular, this refers to the differential effect of imposed temporal frequency, gaze direction, and dual-axis motion on VIMS. Considering the dominance of fore-and-aft motion in simulated and virtual environments this

strongly suggests that future research may benefit from focussing on this type of motion.

One of the topics that may benefit further exploration is the frequency dependence of VIMS. It was mentioned that in the current study, both amplitude and acceleration covaried with frequency. Although other studies have shown that VIMS tends to be more affected by the specific temporal frequency rather than either amplitude or acceleration, the work in this area is thus far limited and future research may benefit from further exploring the relationship between frequency, amplitude, and acceleration in more detail. Ultimately, a better understanding of the frequency dependence may provide valuable information that can subsequently used to design motion scenarios in which particularly nauseogenic motion patterns are avoided. Of course, this may be of particular relevance before habituation has occurred.

Similarly, the study investigating the effect of gaze position on VIMS suggests that reducing redirecting one's gaze and limiting one's gaze near the focus of expansion minimises the occurrence of VIMS. Again, this may be a particular fruitful strategy before habituation has occurred. Unless required for the successful completion of a task, scenarios can be designed in such a way that the amount of gaze shifting required is limited or gaze direction remains focussed near the focus of expansion. It would be of interest to substantiate this finding in other motion environments such as driving simulators.

The unexpected finding of an illusory angular self-motion perception in the absence of angular components in the optic flow as described in chapter 4 (i.e. "visual somatogravic illusion" or "visual SGI"), finally raises some questions with regard to the use of abstract stimuli such as random dot optic flow patterns. In a recent study, the robustness of the visual SGI was confirmed in that more than 80% of the participants perceived this illusory angular motion (Diels et al., 2008). It cannot be ruled out that the occurrence of this illusory self-motion perception may have resulted in a larger degree of sensory conflict rendering the optic flow pattern more nauseogenic. It would be of interest to investigate to what extent this illusion can be ascribed to the absence of polarity cues (i.e. visual information regarding up and down) and horizontal and vertical

structures. The occurrence of the visual SGI further emphasises the importance of integrating the study of self-motion perception with that of VIMS.

A related question concerns the finding that, over time, dual-axis motion resulted in an atypical decrease of VIMS (chapter 6). It would be of interest to investigate the effect of dual- or multi-axis motion using visually more realistic stimuli. It is possible that abstract stimuli may be interpreted as improbable and ultimately disregarded by the brain, a concept recently put forward by Gresty et al. (2003) and referred to as "quarantining". The occurrence of the visual SGI and possibility of a "quarantining" effect illustrate the need to carefully consider the visual stimuli employed and cross-validate findings within different visual environments to establish the robustness of observed effects.

8.3 Final comments

The research presented in this thesis has shown that, compared with angular motion, VIMS resulting from exposure to fore-and-aft motion behaves differently with regard to the effect of frequency, gaze direction, and multi-axis motion. Results obtained using angular motion profiles are therefore of limited value with regard to the occurrence of VIMS in simulators and other VR systems. Future research may therefore benefit from focussing on linear motion in the fore-and-aft axis.

The strong association between VIMS and vection illustrates the fact that VIMS cannot be regarded as an unfortunate consequence of an immature technology. Since Man was not made to travel in cyberspace, VIMS is to be understood as a normal response to an abnormal environment. Future display systems are likely to become increasingly successful in inducing a compelling sense of self-motion and presence, and this can be expected to further increase the incidence and severity of VIMS. In addition, advances in display technology have also led to ever-increasing display sizes in the home entertainment industry and negative side effects are likely to be no longer restricted to the field of professional simulator and VR training. Although VIMS can be dated back to

the area of "Haunted swings", the current work illustrates the many questions that still remain unanswered with regard to VIMS.

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Appendix 1

Motion Sickness Susceptibility Questionnaire

This questionnaire is designed to find out how susceptible you are and what sorts of motion are most effective in causing that sickness. Sickness here means feeling quite queasy or nauseated or actually vomiting.

After some background questions, the questionnaire consists of two sections:

Section A is concerned with your **childhood** experiences of travel and motion sickness, that is, before the age of 12 years.

Section B is concerned with your experiences of travel and motion sickness **over the last 10 years.**

The correct way to answer each question is explained in the body of the questionnaire. It is important that you answer every question.

Thank you for your help.

Background Questions

1. Please state your age _____ years
2. Please state your gender (please circle) Male Female
3. Please state your current occupation

   _____

4. Do you regard yourself as susceptible to motion sickness? (please circle)

   Not at all Slightly Moderately Very much so

Section A: Your CHILDHOOD experience only (before 12 years of age)

For each of the following types of transport or entertainment please indicate:

5. As a **child (before age 12),** how often you **travelled** or **experienced** (tick boxes):

	Never	1 to 4 trips	5 to 10 trips	11 or more trips
Cars				
Buses or Coaches				
Trains				
Aircraft				
Small Boats				
Ships, e.g. Channel Ferries				
Swings				
Roundabouts: playgrounds				
Big Dippers, Funfair Rides				
Cinema				
	0	1	2	3

6. As a **child (before age 12),** how often you **felt sick or nauseated** (tick boxes):

	Never	Rarely	Sometimes	Frequently	Always
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings					
Roundabouts: playgrounds					
Big Dippers, Funfair Rides					
Cinema					
	0	1	2	3	4

7. As a **child (before age 12),** how often you **vomited** (tick boxes):

	Never	**Rarely**	**Sometimes**	**Frequently**	**Always**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings					
Roundabouts: playgrounds					
Big Dippers, Funfair Rides					
Cinema					
	0	1	2	3	4

Section B: Your experience over the last 10 years (approximately).

For each of the following types of transport or entertainment please indicate:

8. Over the **last 10 years**, how often you **travelled** or **experienced** (tick boxes):

	Never	1 to 4 trips	5 to 10 trips	11 or more trips
Cars				
Buses or Coaches				
Trains				
Aircraft				
Small Boats				
Ships, e.g. Channel Ferries				
Swings				
Roundabouts: playgrounds				
Big Dippers, Funfair Rides				
Cinema				
	0	1	2	3

9. Over the **last 10 years,** how often you **felt sick or nauseated** (tick boxes):

	Never	Rarely	Sometimes	Frequently	Always
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings					
Roundabouts: playgrounds					
Big Dippers, Funfair Rides					
Cinema					
	0	1	2	3	4

10. Over the **last 10 years,** how often you **vomited** (tick boxes):

	Never	**Rarely**	**Sometimes**	**Frequently**	**Always**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings					
Roundabouts: playgrounds					
Big Dippers, Funfair Rides					
Cinema					
	0	1	2	3	4

Appendix 2

MSQ

PRE

Participant _____ Date_____ Condition_____

Instructions: Please tick the appropriate box that corresponds to the level of symptoms that you are experiencing **right now**.

	No	Slight	Moderate	Severe
	0	1	2	3
1. General discomfort	☐	☐	☐	☐
2. Fatigue	☐	☐	☐	☐
3. Headache	☐	☐	☐	☐
4. Eyestrain	☐	☐	☐	☐
5. Difficulty focussing	☐	☐	☐	☐
6.a Increased salivation	☐	☐	☐	☐
b Decreased salivation	☐	☐	☐	☐
7. Sweating	☐	☐	☐	☐
8. Nausea	☐	☐	☐	☐
9. Difficulty concentrating	☐	☐	☐	☐
10. Fullness of head	☐	☐	☐	☐
11. Blurred vision	☐	☐	☐	☐
12. Dizzy (eyes open)	☐	☐	☐	☐
13. Dizzy (eyes closed)	☐	☐	☐	☐
14. Vertigo*	☐	☐	☐	☐
15. Stomach awareness**	☐	☐	☐	☐
16. Burping	☐	☐	☐	☐
17. Boredom	☐	☐	☐	☐
18. Drowsiness	☐	☐	☐	☐
19. Mental depression	☐	☐	☐	☐
20. Visual flashbacks***	☐	☐	☐	☐
21. Faintness	☐	☐	☐	☐
22. Aware of breathing	☐	☐	☐	☐
23. Loss of appetite	☐	☐	☐	☐
24. Increased appetite	☐	☐	☐	☐
25. Desire to move bowels	☐	☐	☐	☐
26. Vomiting	Yes	No		
27. Other	☐	☐	☐	☐

* Vertigo is experienced as loss of orientation with respect to vertical upright.
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.
*** Visual flashbacks: illusory (motion) aftereffects reminiscent of sensations when in the simulator.

POST

Participant _____ Date_____ Condition_____

Instructions: Please tick the appropriate box that corresponds to the level of symptoms that you were experiencing **just before the session was ended.**

	No 0	Slight 1	Moderate 2	Severe 3
1. General discomfort	☐	☐	☐	☐
2. Fatigue	☐	☐	☐	☐
3. Headache	☐	☐	☐	☐
4. Eyestrain	☐	☐	☐	☐
5. Difficulty focussing	☐	☐	☐	☐
6.a Increased salivation	☐	☐	☐	☐
b Decreased salivation	☐	☐	☐	☐
7. Sweating	☐	☐	☐	☐
8. Nausea	☐	☐	☐	☐
9. Difficulty concentrating	☐	☐	☐	☐
10. Fullness of head	☐	☐	☐	☐
11. Blurred vision	☐	☐	☐	☐
12. Dizzy (eyes open)	☐	☐	☐	☐
13. Dizzy (eyes closed)	☐	☐	☐	☐
14. Vertigo*	☐	☐	☐	☐
15. Stomach awareness**	☐	☐	☐	☐
16. Burping	☐	☐	☐	☐
17. Boredom	☐	☐	☐	☐
18. Drowsiness	☐	☐	☐	☐
19. Mental depression	☐	☐	☐	☐
20. Visual flashbacks***	☐	☐	☐	☐
21. Faintness	☐	☐	☐	☐
22. Aware of breathing	☐	☐	☐	☐
23. Loss of appetite	☐	☐	☐	☐
24. Increased appetite	☐	☐	☐	☐
25. Desire to move bowels	☐	☐	☐	☐
26. Vomiting	Yes	No		
27. Other	☐	☐	☐	☐

* Vertigo is experienced as loss of orientation with respect to vertical upright.
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.
*** Visual flashbacks: illusory (motion) aftereffects reminiscent of sensations when in the simulator.

Appendix 3

POST
Participant _____ Date _____ Condition _____

Whilst watching the moving images, did you get the feeling of motion?
That is, did you experience a compelling sensation of self-motion as though you were actually moving?

Please tick the appropriate box below:

1. Overall

Not at all						**Very much so**
1	**2**	**3**	**4**	**5**	**6**	**7**
☐	☐	☐	☐	☐	☐	☐

In case you were experiencing a sensation of self-motion in different directions, please indicate below how compelling you found each of these directions

Please tick the appropriate box below:

2. Forward direction

Not at all						**Very much so**
1	**2**	**3**	**4**	**5**	**6**	**7**
☐	☐	☐	☐	☐	☐	☐

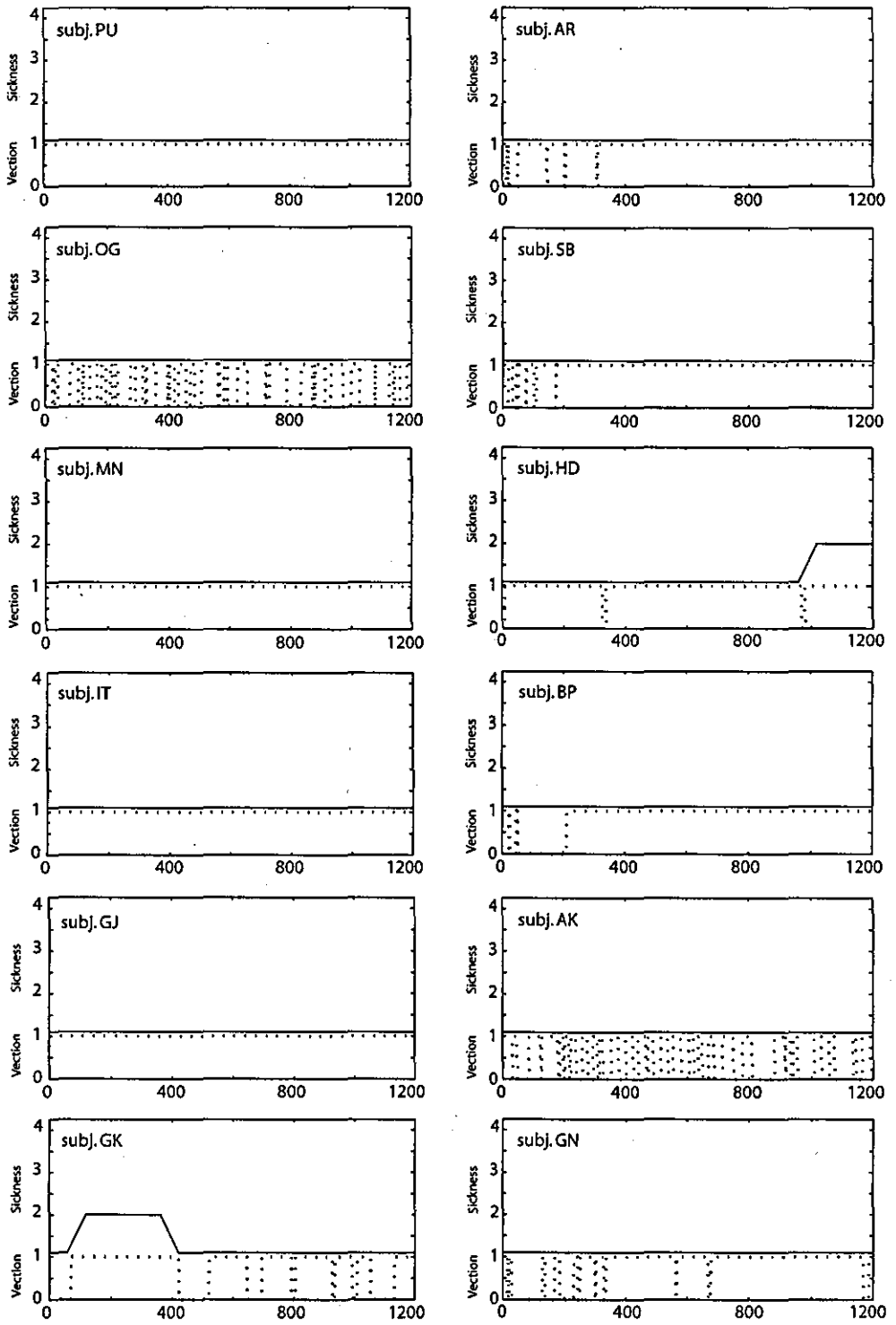
3. Backward direction

Not at all						**Very much so**
1	**2**	**3**	**4**	**5**	**6**	**7**
☐	☐	☐	☐	☐	☐	☐

4. Roll direction / rocking motion

Not at all						**Very much so**
1	**2**	**3**	**4**	**5**	**6**	**7**
☐	☐	☐	☐	☐	☐	☐

Appendix 4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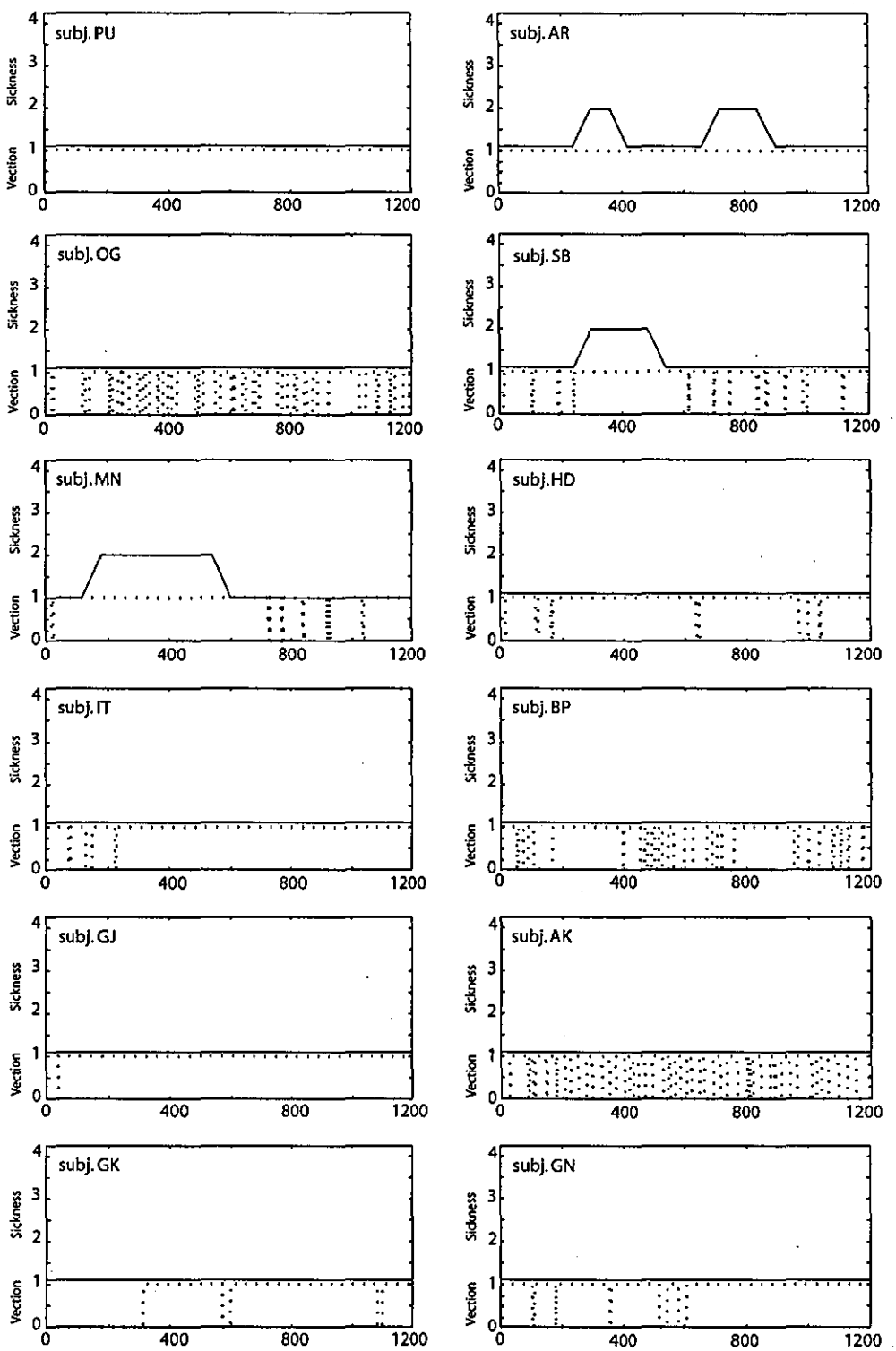
subj. GK
subj. GN
Sickness
Vection
0
400
800
1200
1
2
3
4

Appendix 5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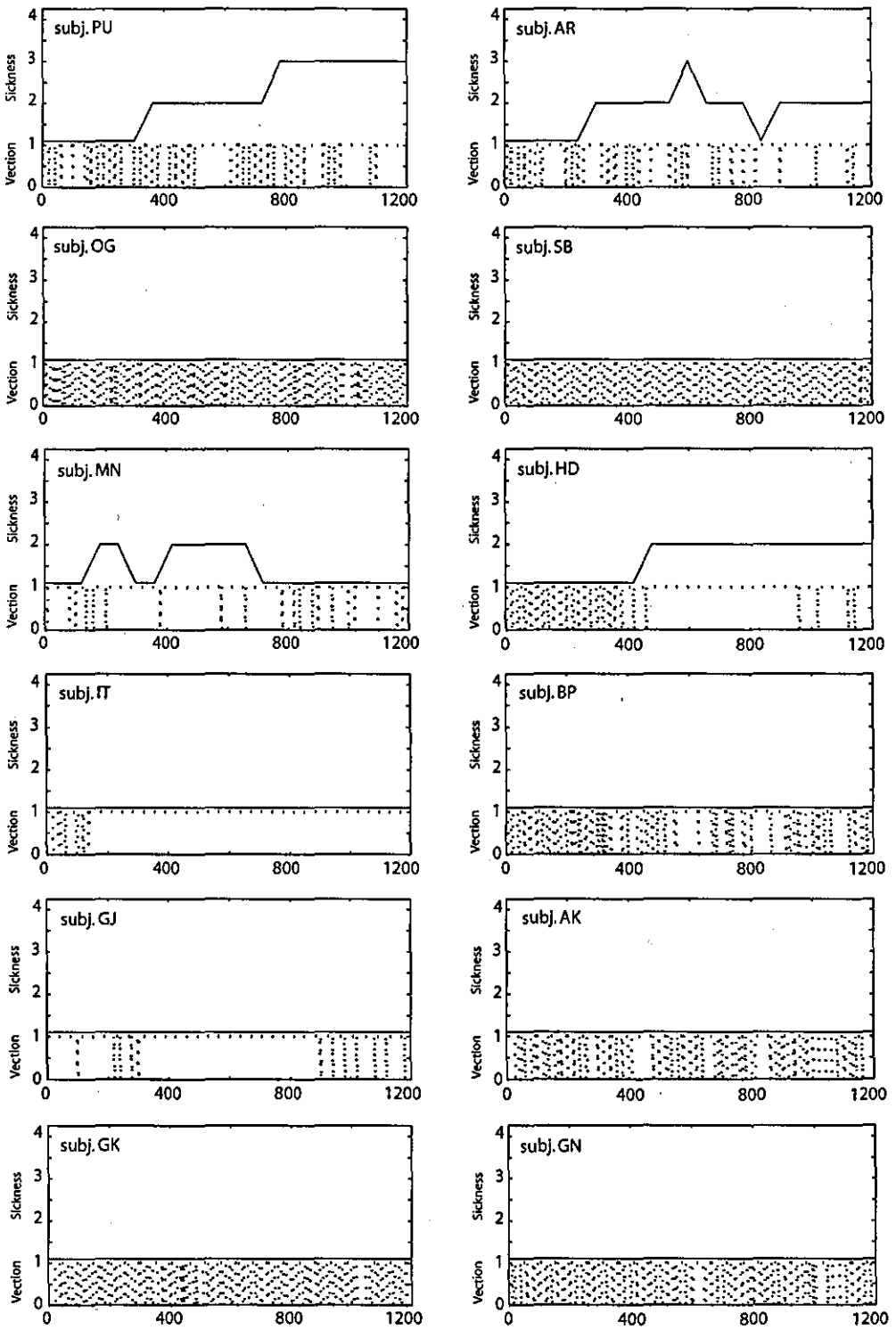
subj. GK
subj. GN
Sickness
Vection
0
1
2
3
4
0
400
800
1200

Appendix 6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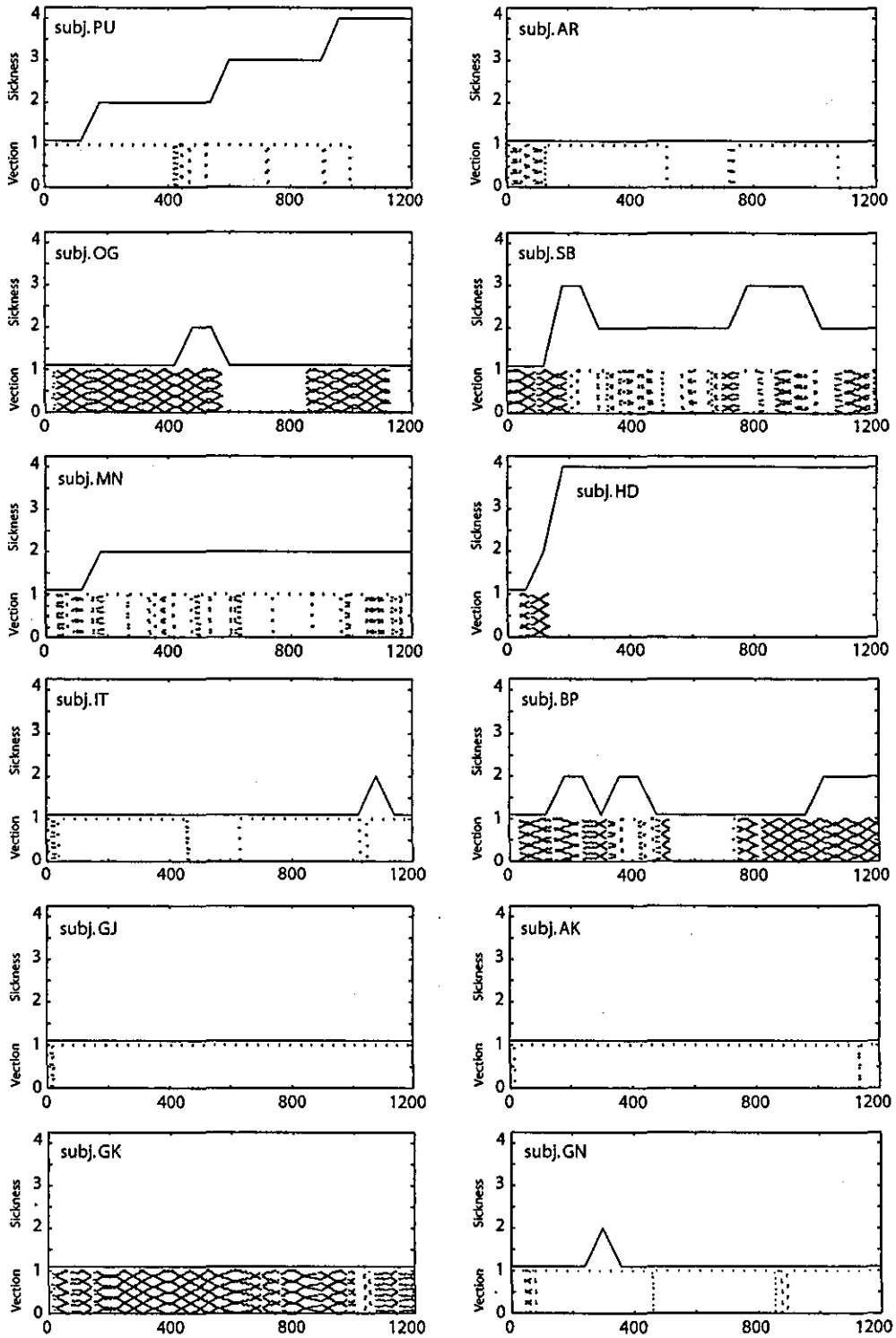
subj. GN
Sickness
Vection
0
400
800
1200
1
2
3
4

Appendix 7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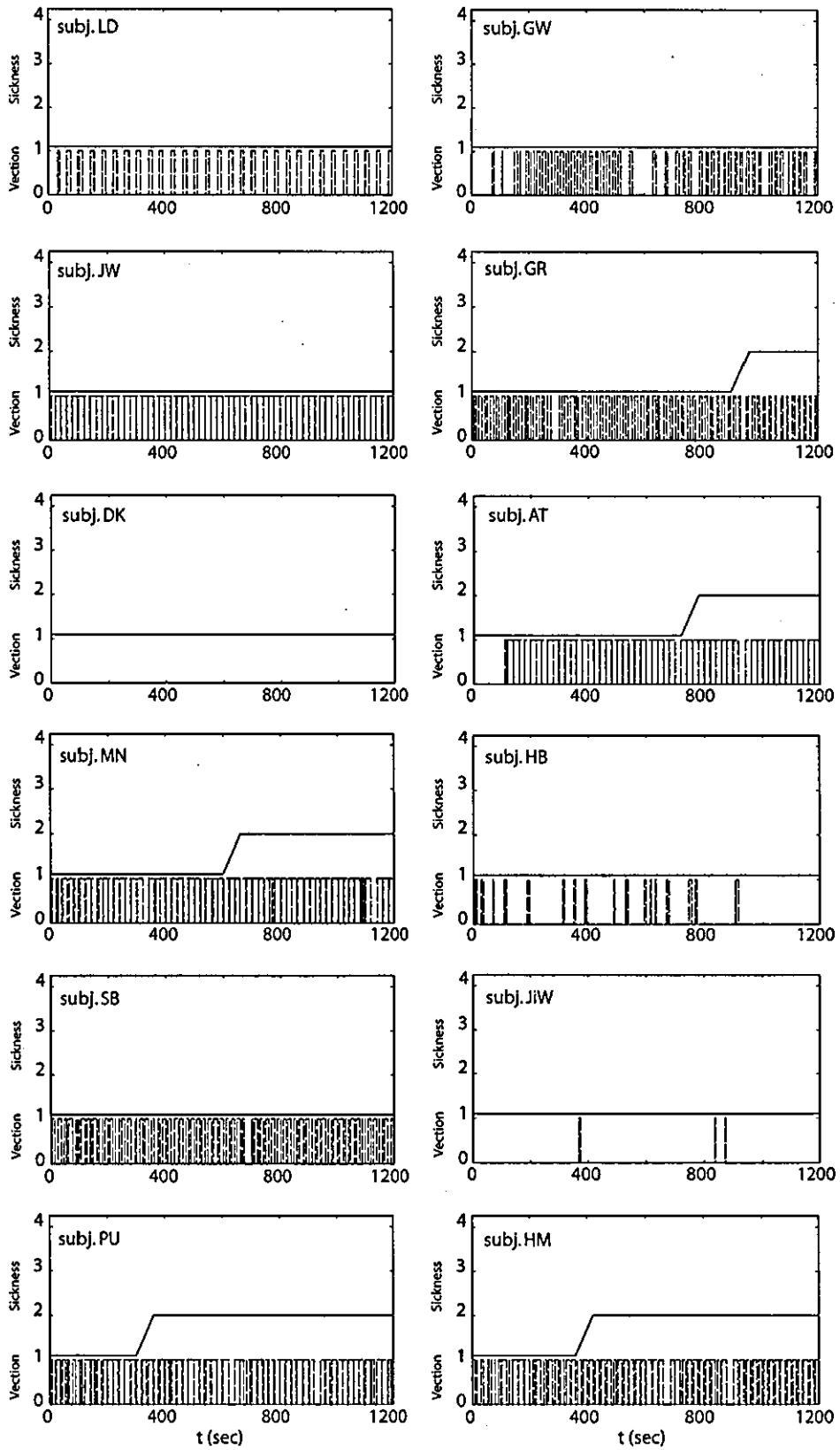
subj. GN
Sickness
Vection
0
1
2
3
4
400
800
1200

Appendix 8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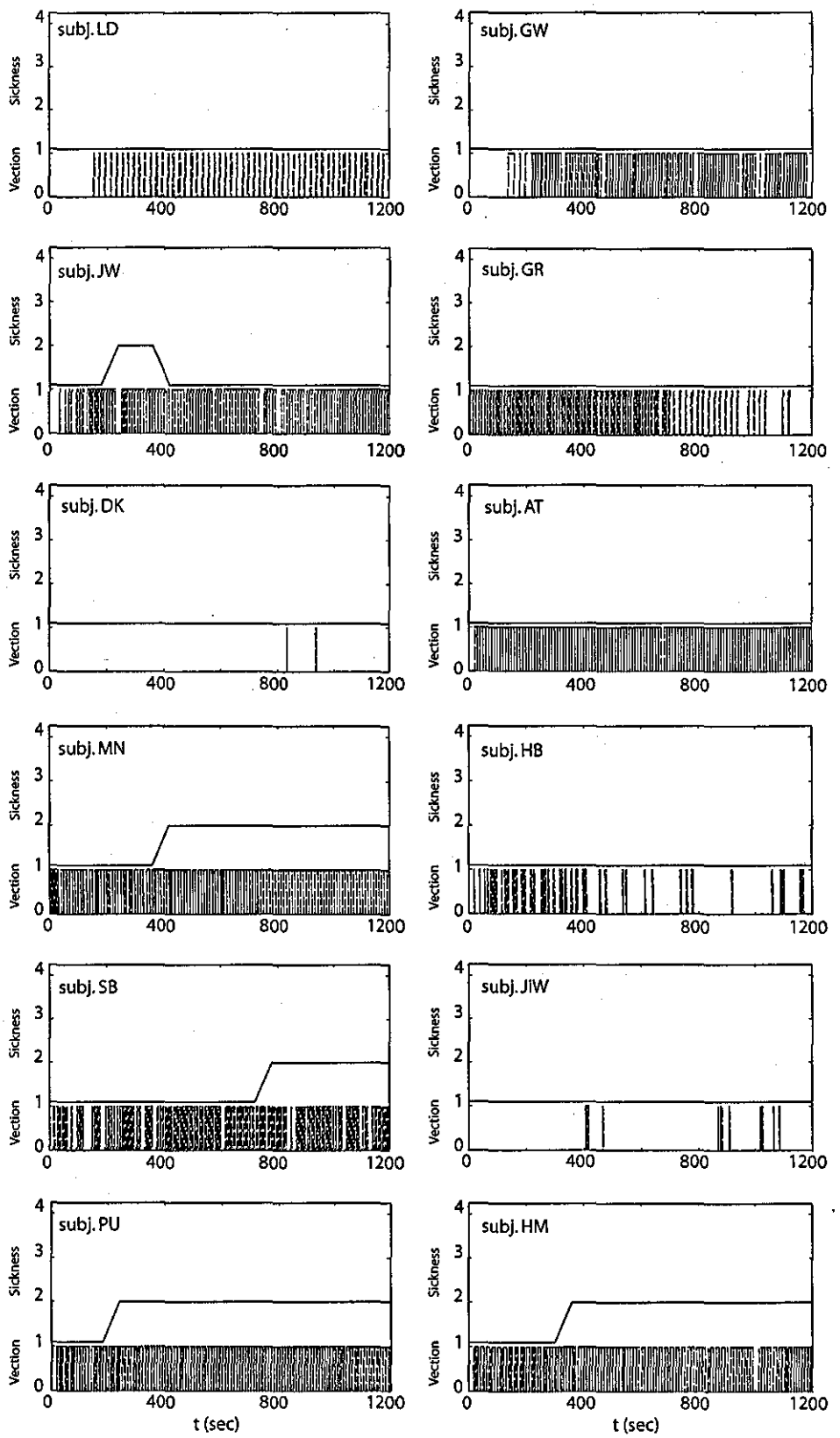
subj. HM
Sickness
Vection
0
1
2
3
4
0
400
800
1200
t (sec)

Appendix 9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subj. PU
subj. HM
Sickness
Vection
0
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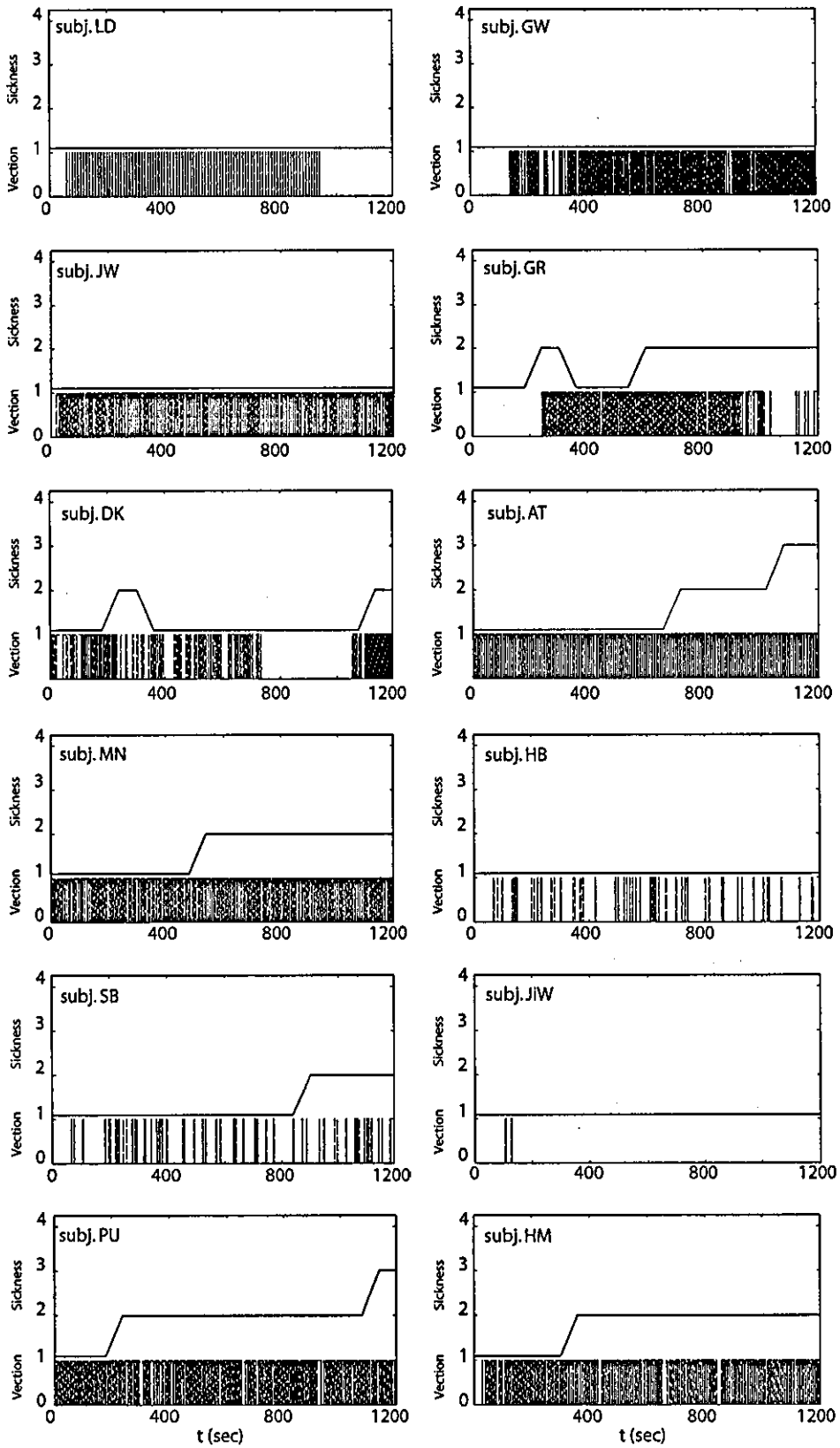
2
3
4
0
400
800
1200
t (sec)

Appendix 10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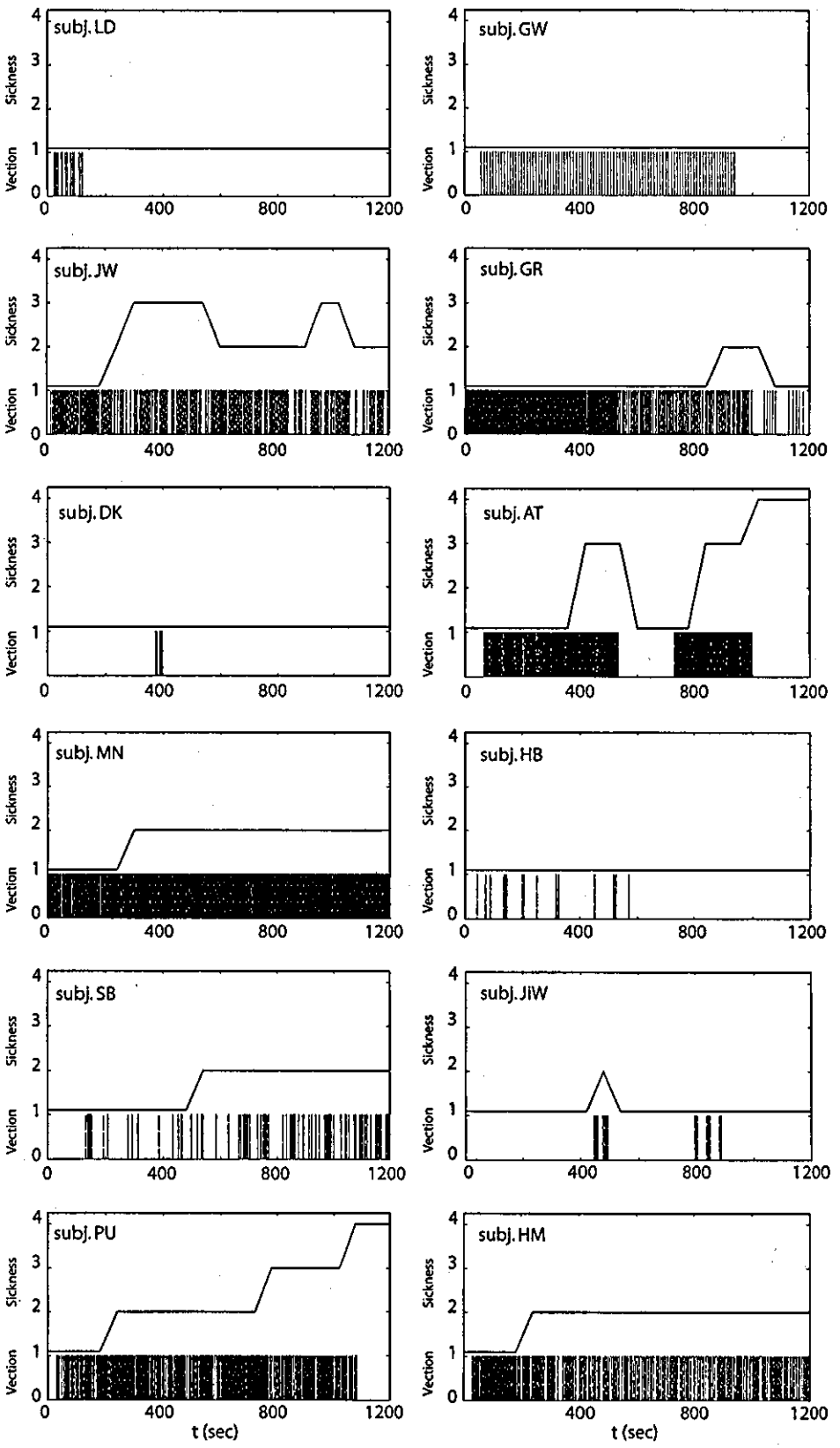
subj. PU
subj. HM
Sickness
Vection
0
400
800
1200
t (sec)

Appendix 11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subj. SB
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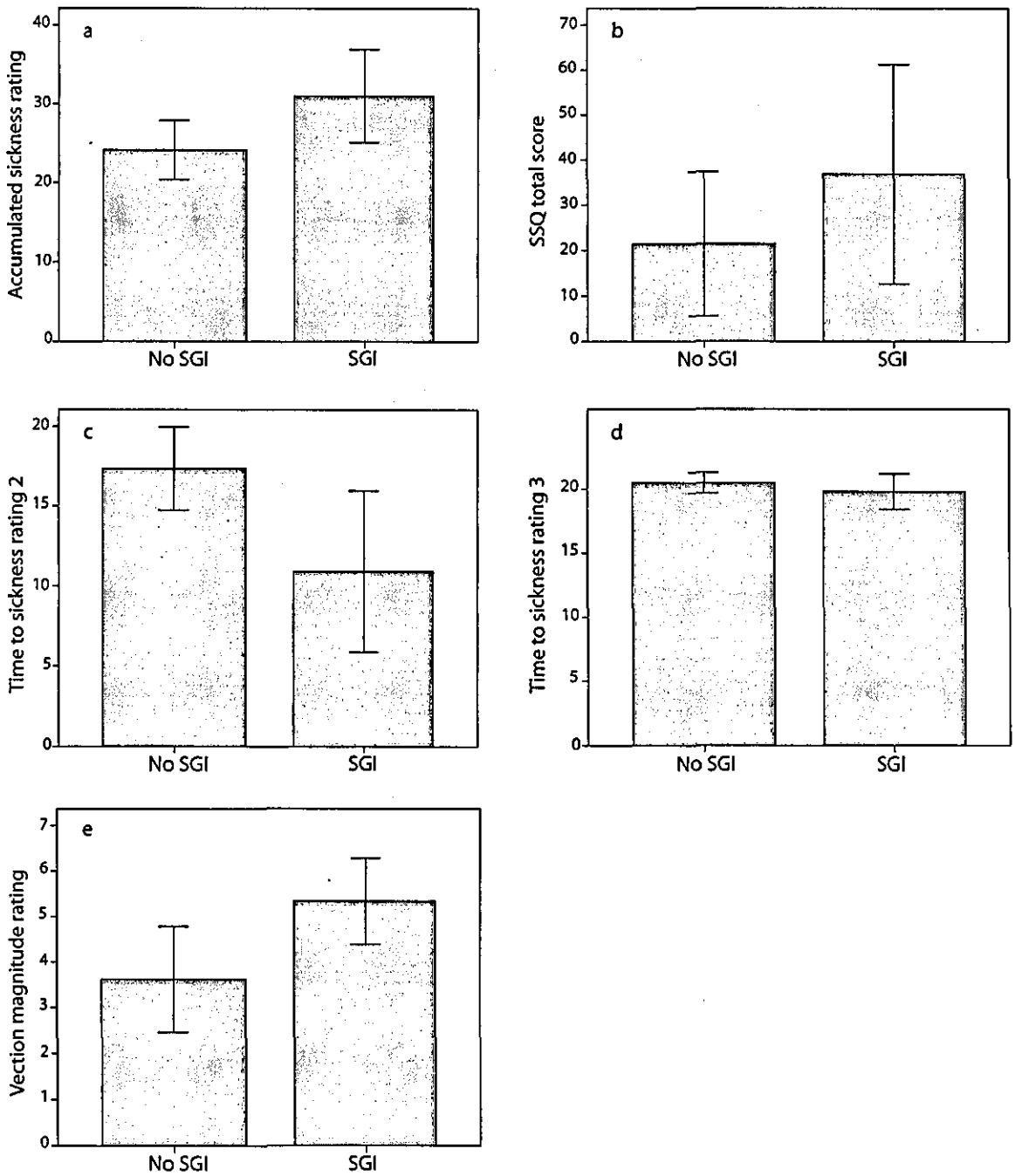
subj. HM
Sickness
Vection
0
1
2
3
4
400
800
1200
t (sec)

Appendix 12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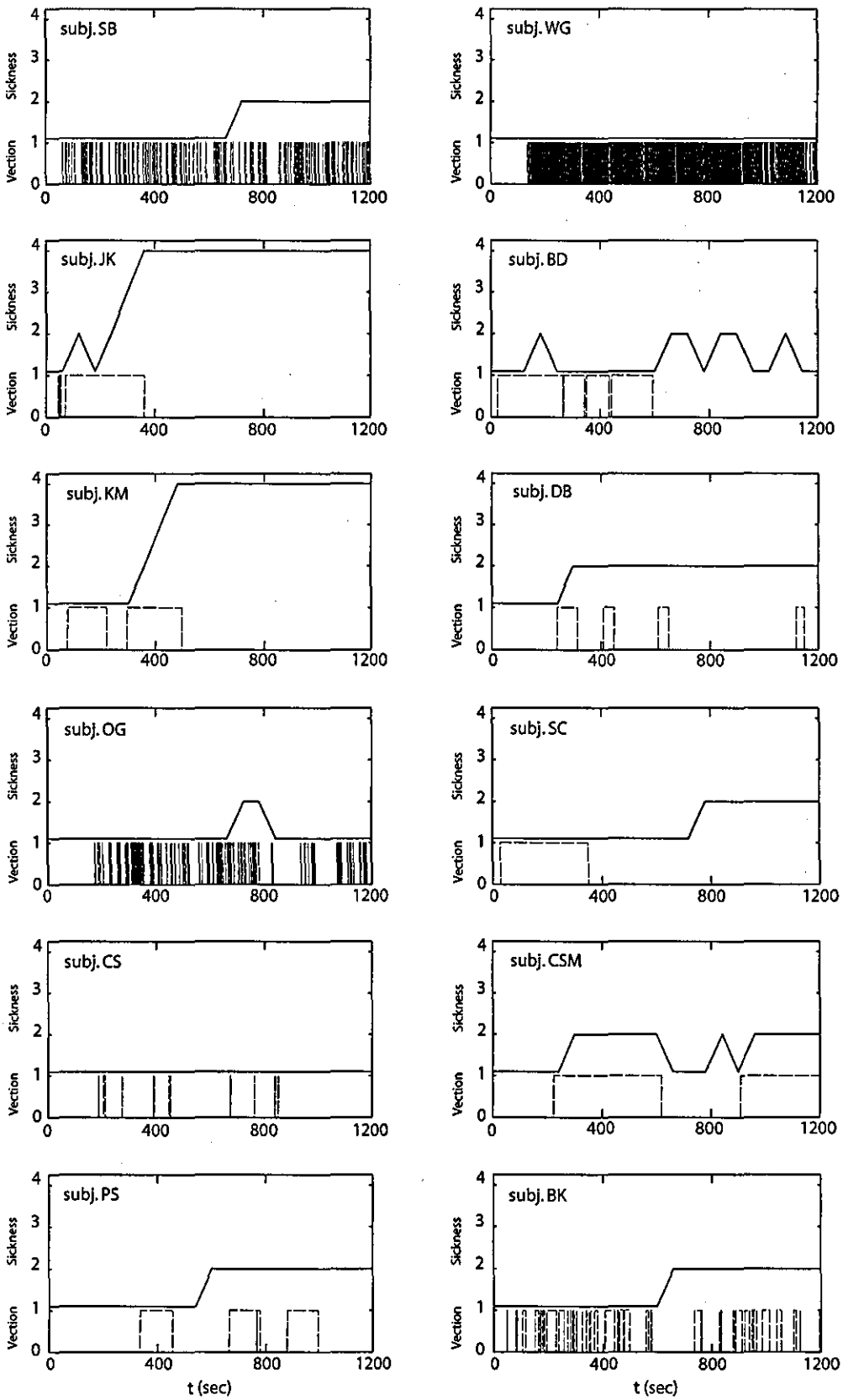
Accumulated sickness rating
40
30
20
10
0
No SGI
SGI
b
SSQ total score
70
60
50
40
30
20
10
0
No SGI
SGI
c
Time to sickness rating 2
20
15
10
5
0
No SGI
SGI
d
Time to sickness rating 3
20
15
10
5
0
No SGI
SGI
e
Vection magnitude rating
7
6
5
4
3
2
1
0
No SGI
SGI

Appendix 13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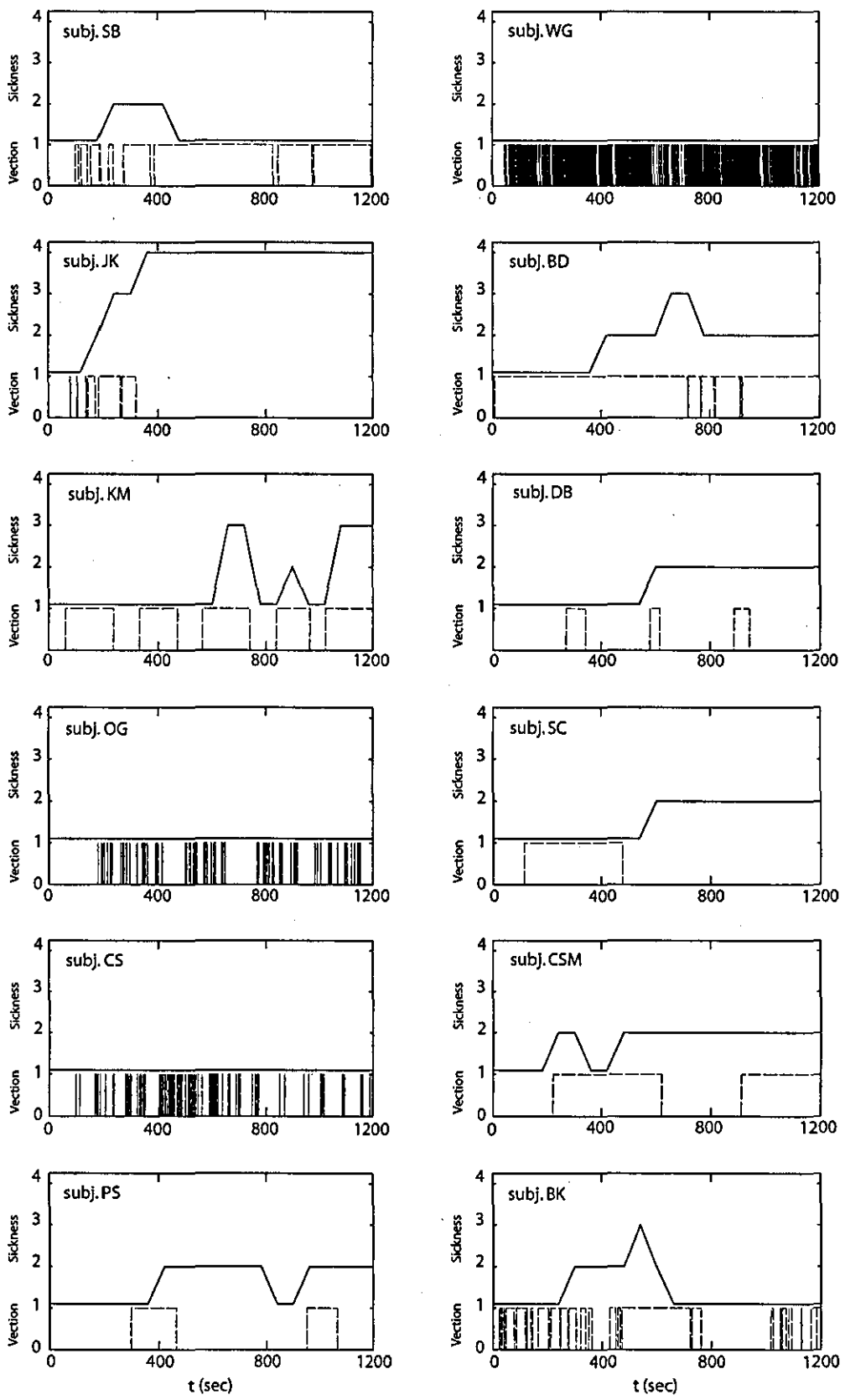
subj. WG
subj. JK
subj. BD
subj. KM
subj. DB
subj. OG
subj. SC
subj. CS
subj. CSM
subj. PS
subj. BK
Sickness
Vection
0
1
2
3
4
400
800
1200
t (sec)

Appendix 14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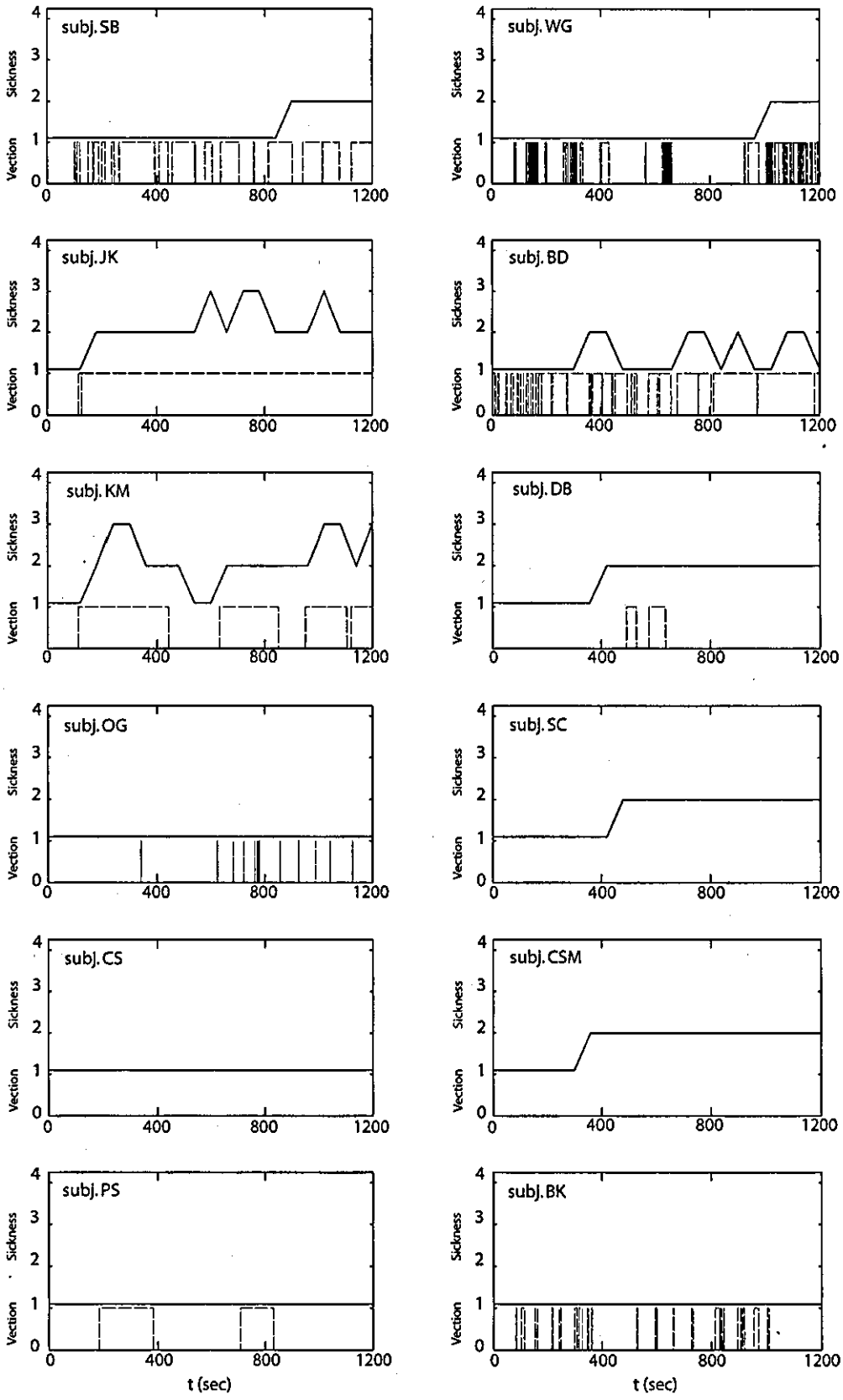
subj. BD
subj. KM
subj. DB
subj. OG
subj. SC
subj. CS
subj. CSM
subj. PS
subj. BK
Sickness
Vection
0
1
2
3
4
400
800
1200
t (sec)

Appendix 15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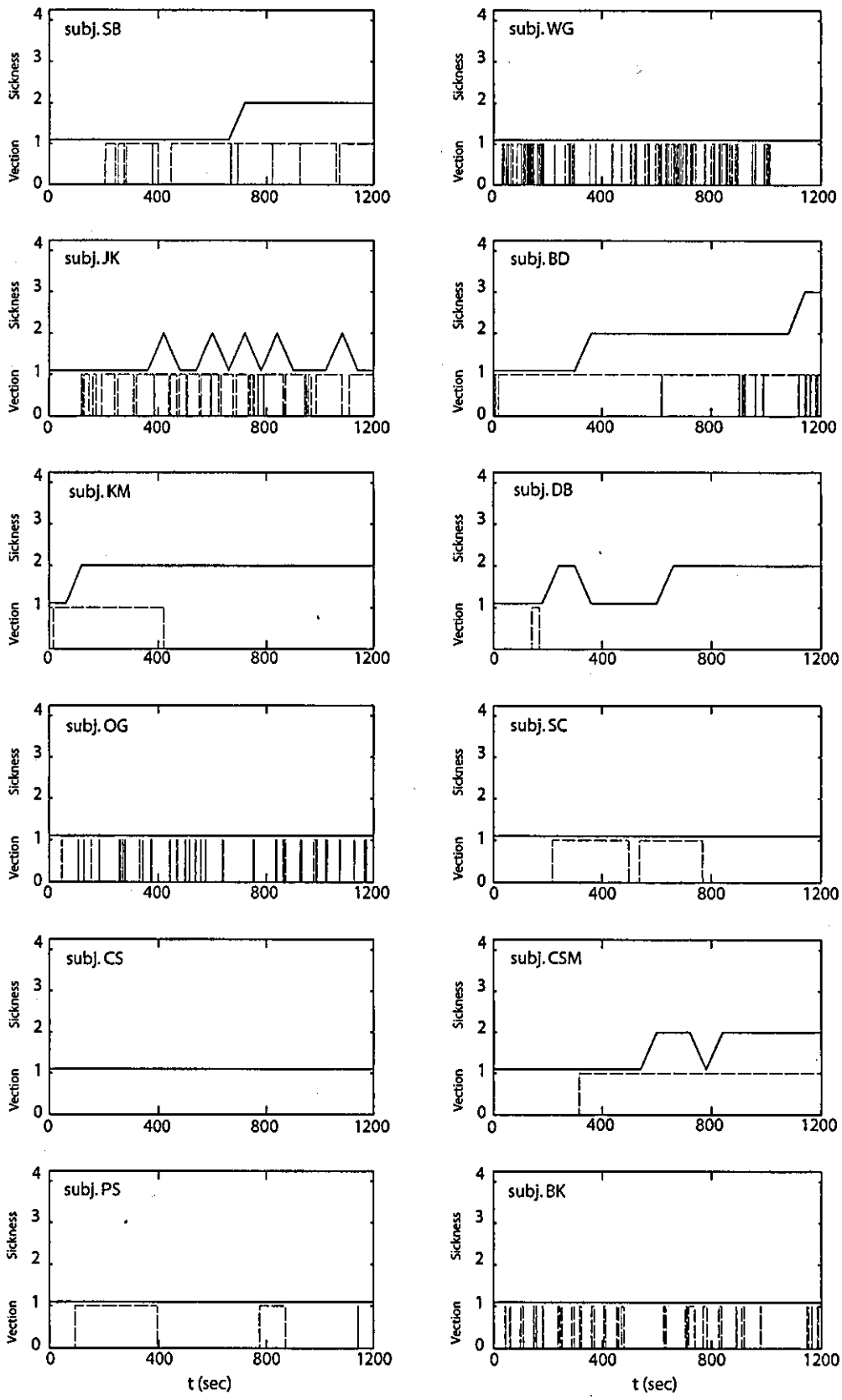
subj. JK
subj. BD
subj. KM
subj. DB
subj. OG
subj. SC
subj. CS
subj. CSM
subj. PS
subj. BK
Sickness
Vection
0
1
2
3
4
400
800
1200
t (sec)

Appendix 16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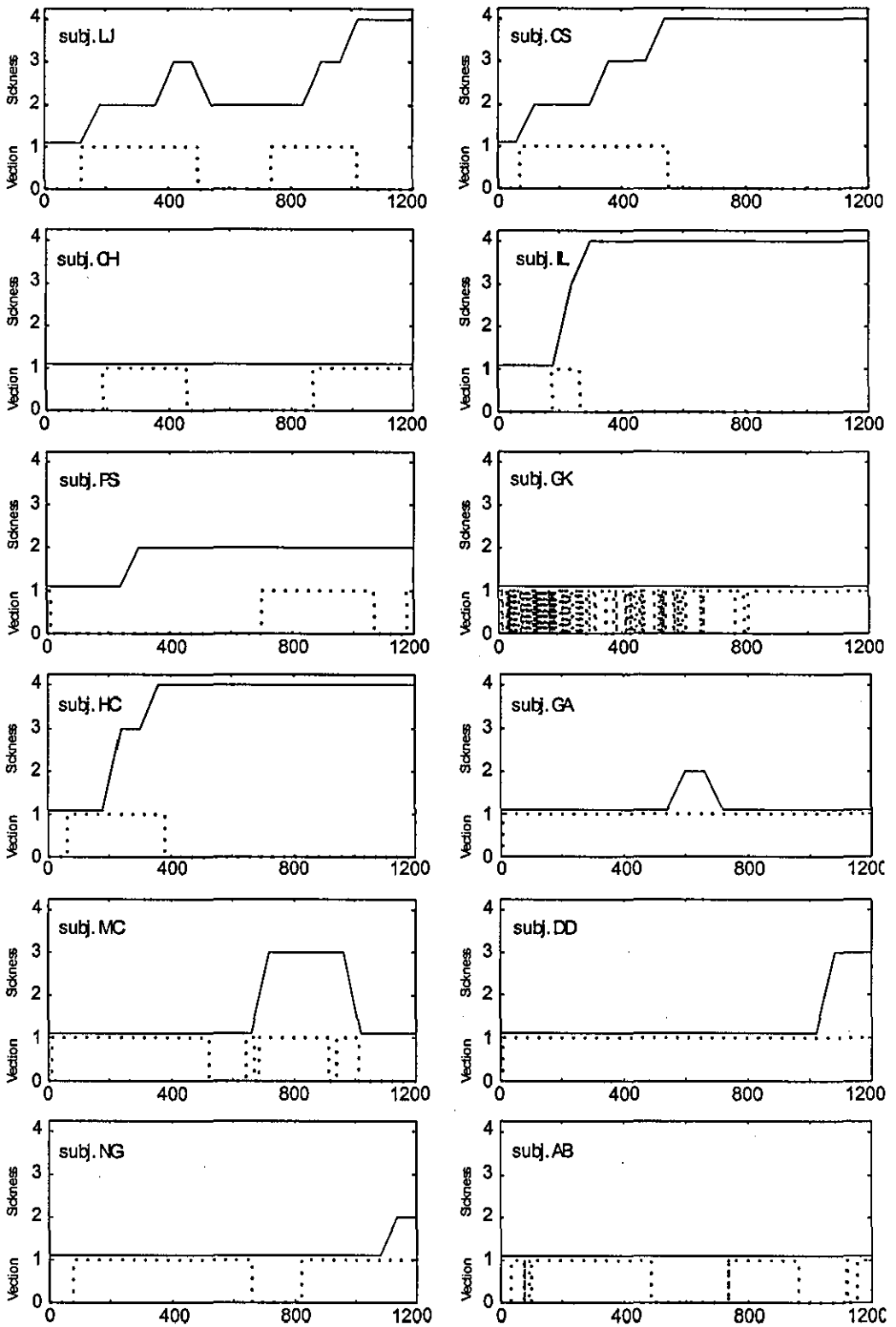
subj. BD
subj. KM
subj. DB
subj. OG
subj. SC
subj. CS
subj. CSM
subj. PS
subj. BK
Sickness
Vection
0
1
2
3
4
400
800
1200
t (sec)

Appendix 17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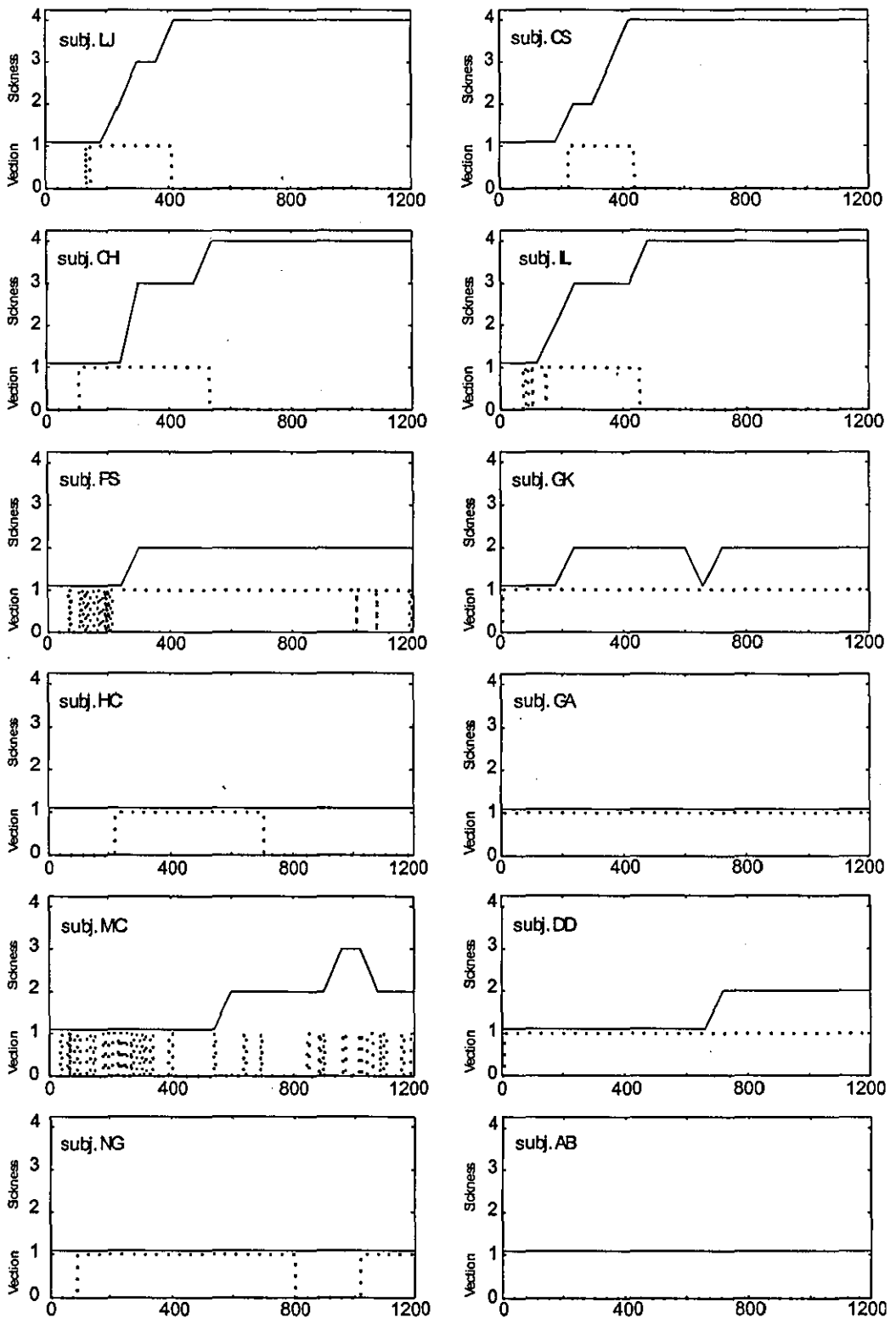
subj. CH
subj. IL
subj. PS
subj. GK
subj. HC
subj. GA
subj. MC
subj. DD
subj. NG
subj. AB
Sickness
Vection
0
400
800
1200

Appendix 18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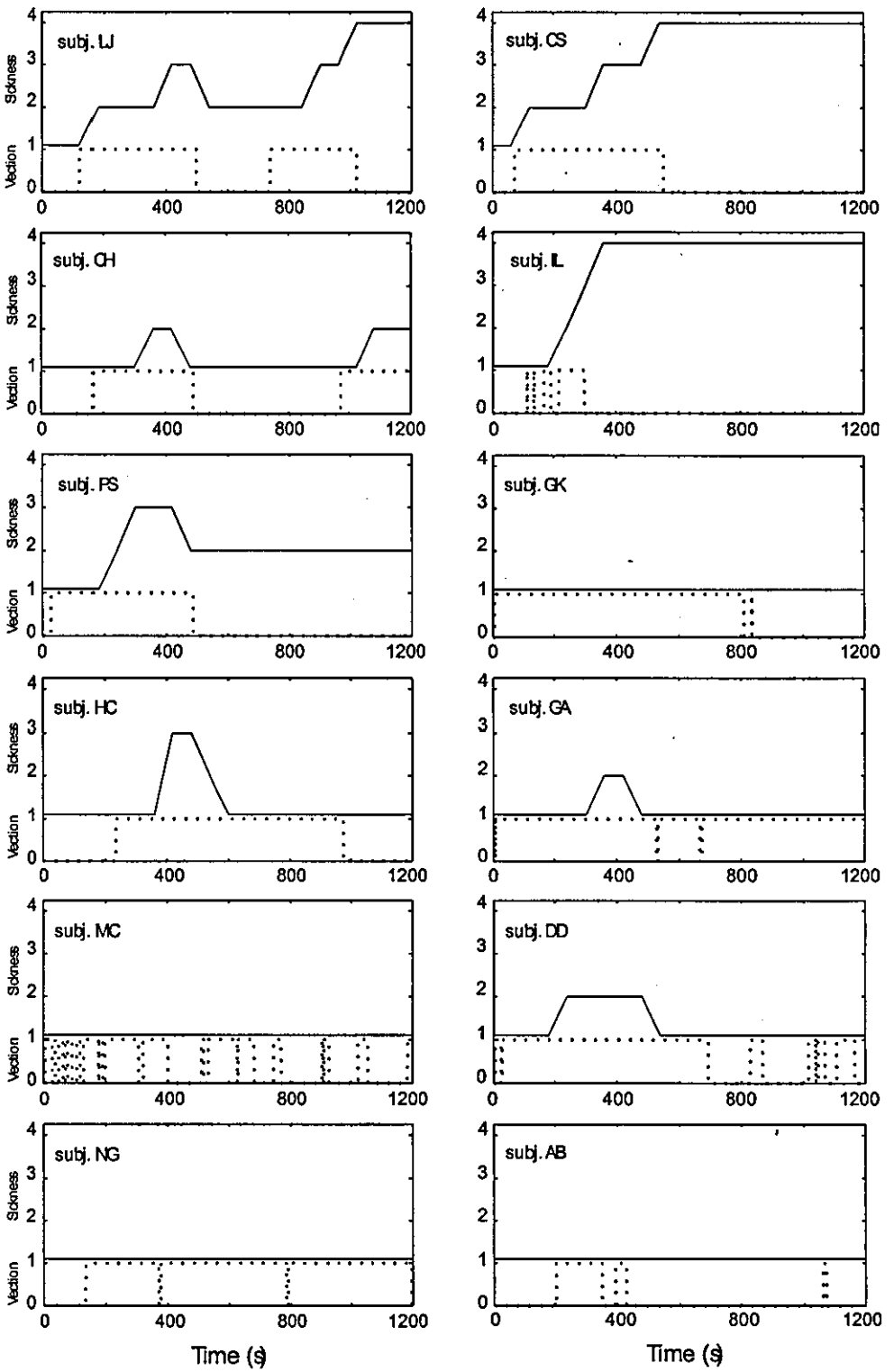
subj. CH
subj. IL
subj. PS
subj. GK
subj. HC
subj. GA
subj. MC
subj. DD
subj. NG
subj. AB
Sickness
Vection
0
1
2
3
4
0
400
800
1200

Appendix 19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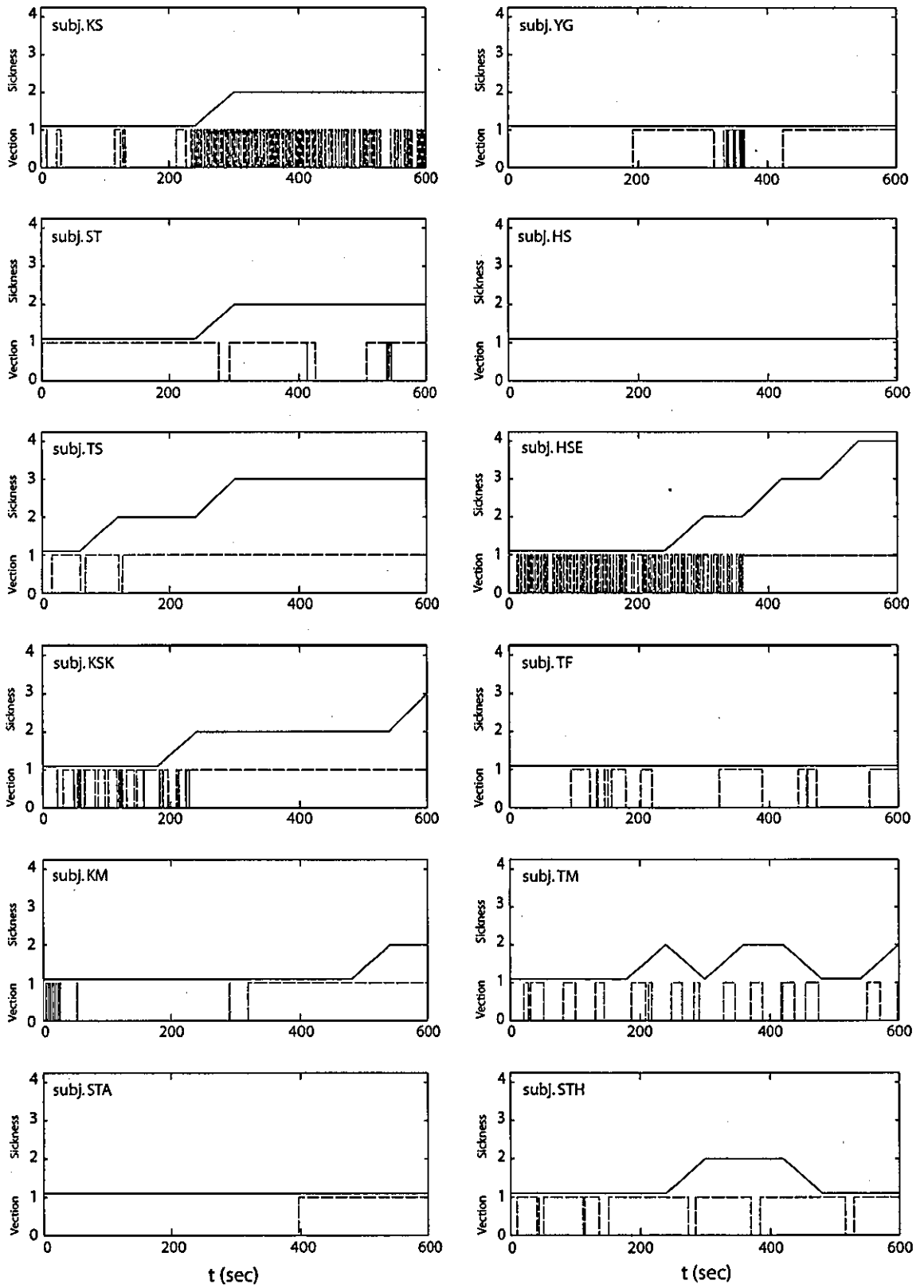
subj. CH
subj. IL
subj. PS
subj. GK
subj. HC
subj. GA
subj. MC
subj. DD
subj. NG
subj. AB
Sickness
Vection
0
1
2
3
4
0
400
800
1200
Time (s)

Appendix 20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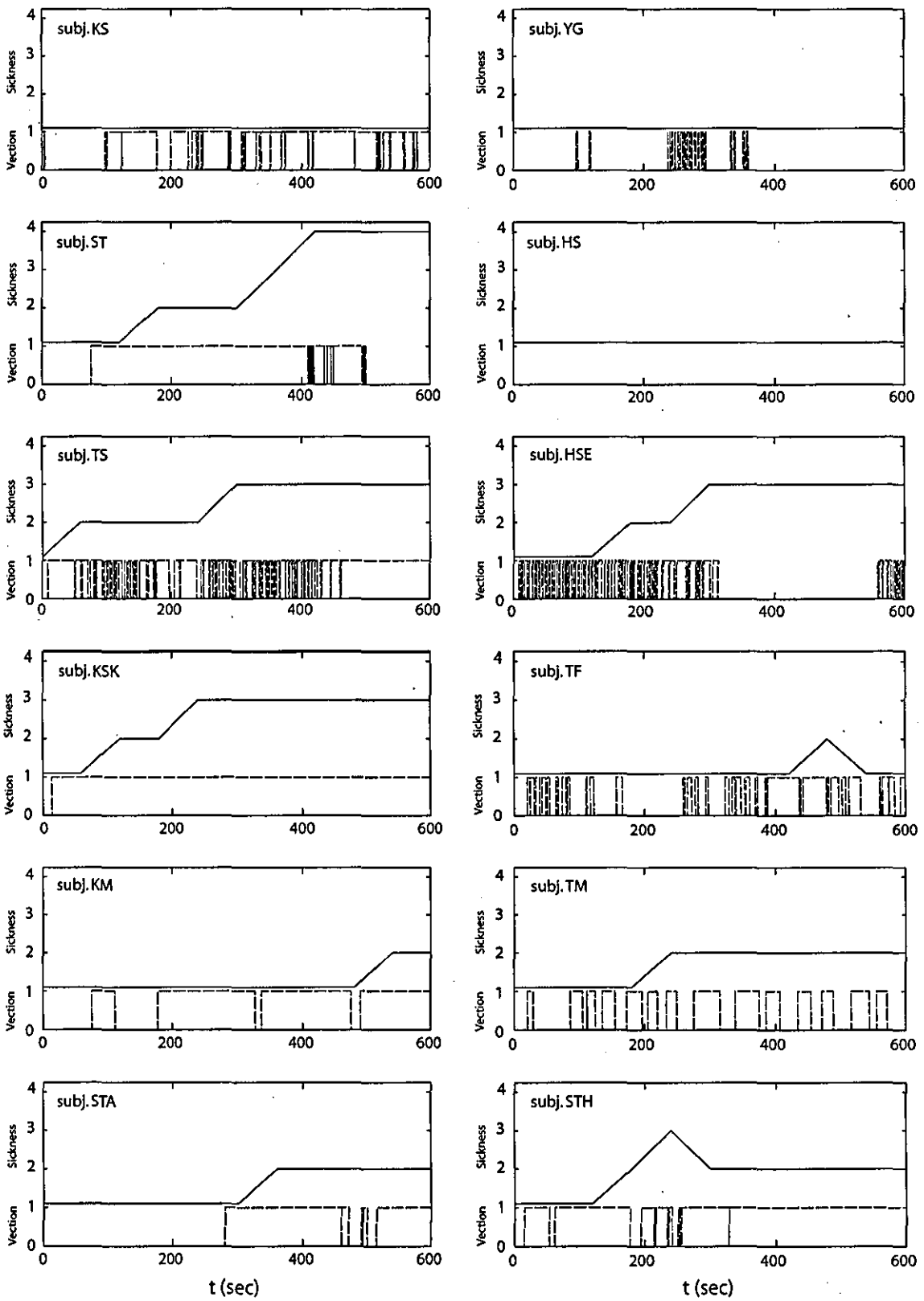
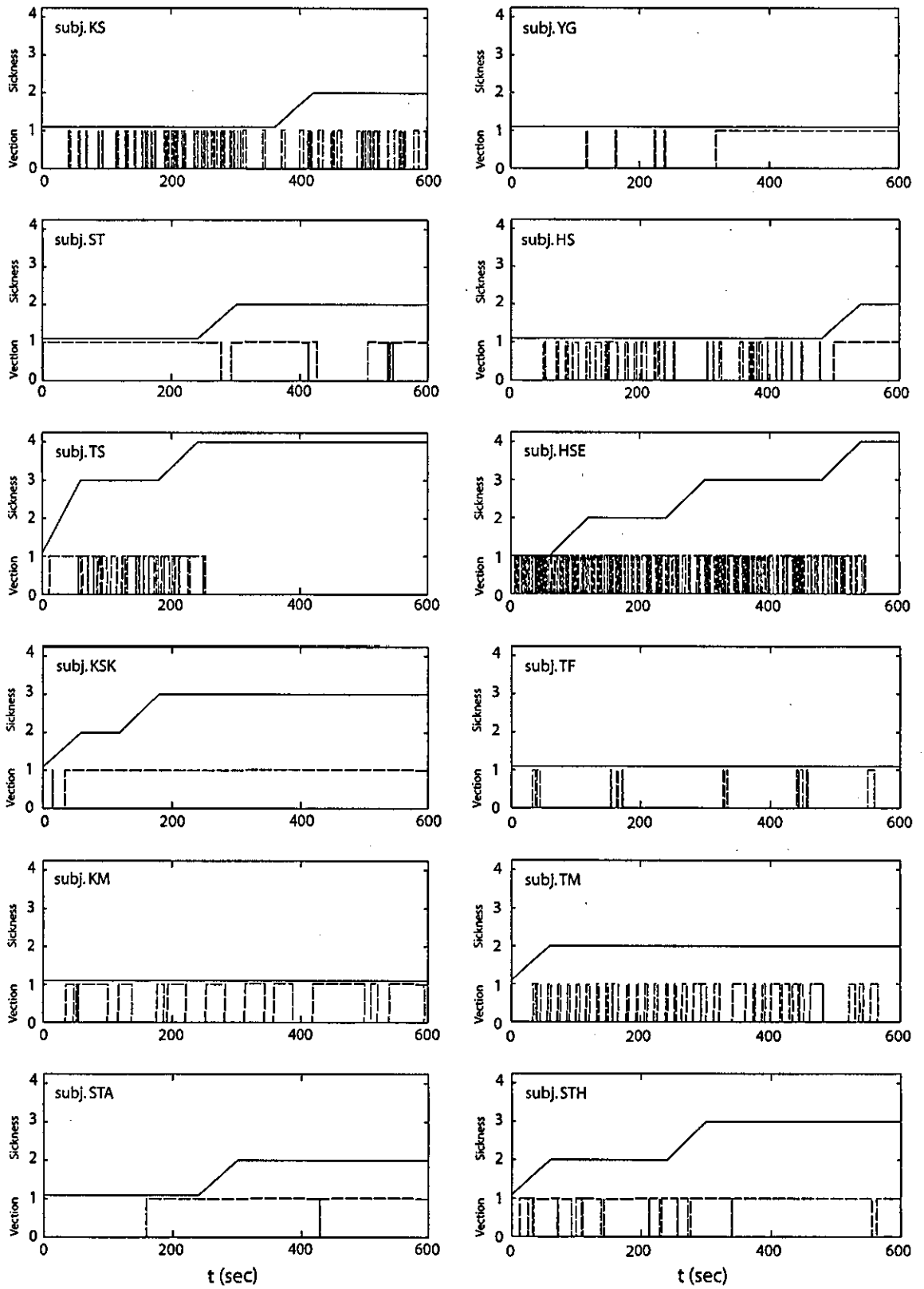
subj. YG
subj. ST
subj. HS
subj. TS
subj. HSE
subj. KSK
subj. TF
subj. KM
subj. TM
subj. STA
subj. STH
Sickness
Vection
0
1
2
3
4
0
200
400
600
t (sec)

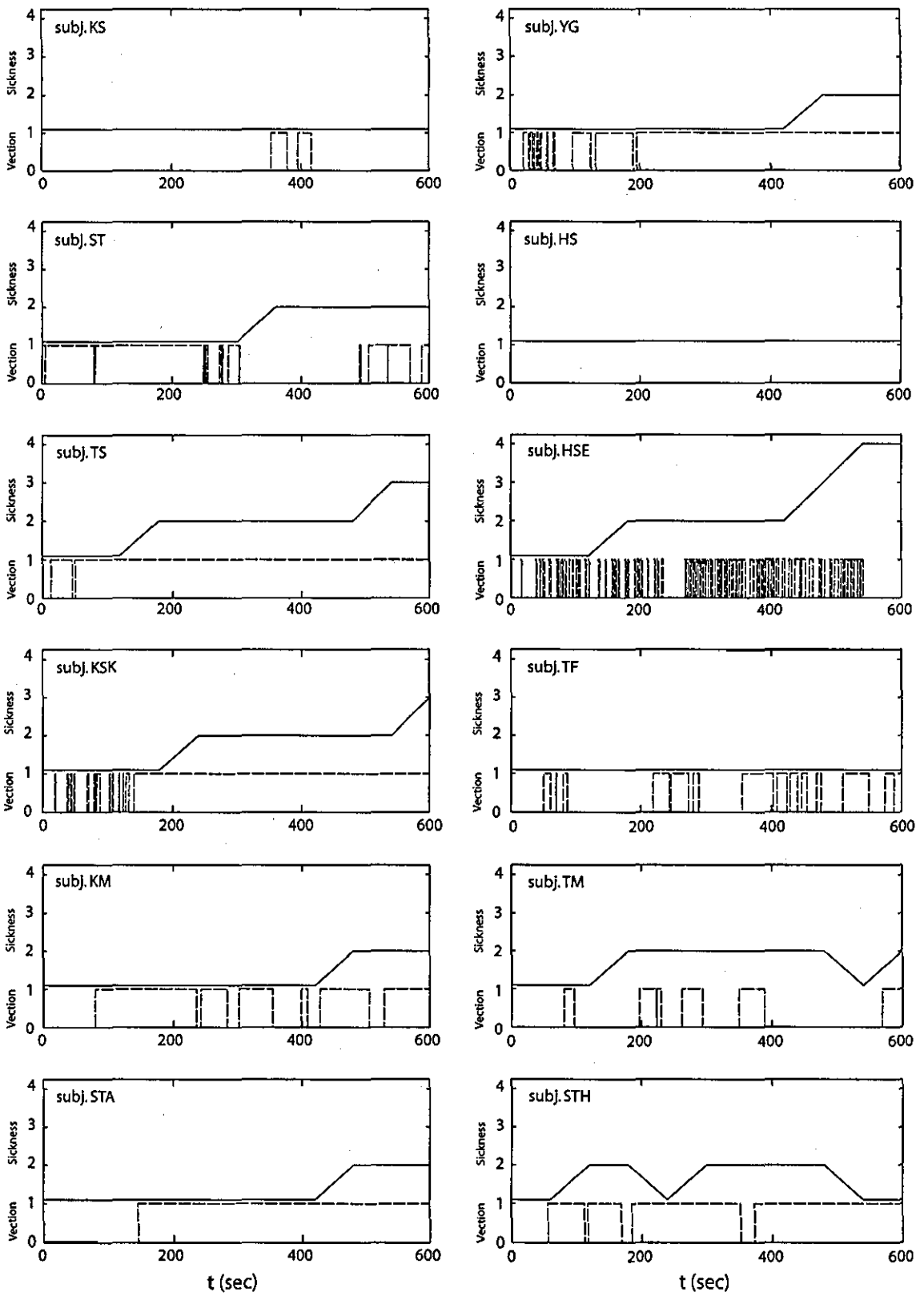
Appendix 21


subj.KS
subj.YG
subj.ST
subj.HS
subj.TS
subj.HSE
subj.KSK
subj.TF
subj.KM
subj.TM
subj.STA
subj.STH
Sickness
Vection
0
1
2
3
4
0
200
400
600
t (sec)

Appendix 22


subj. KS
subj. YG
subj. ST
subj. HS
subj. TS
subj. HSE
subj. KSK
subj. TF
subj. KM
subj. TM
subj. STA
subj. STH
Sickness
Vection
0
1
2
3
4
0
200
400
600
t (sec)

Appendix 23


subj. KS
subj. YG
subj. ST
subj. HS
subj. TS
subj. HSE
subj. KSK
subj. TF
subj. KM
subj. TM
subj. STA
subj. STH
Sickness
Vection
0
1
2
3
4
0
200
400
600
t (sec)

Appendix 24

MSQ (Japanese)

PRE

Participant _____ Date_____ Condition_____

今現在の、あなたの症状について、該当するボックスにチェックしてください。

	症状無	軽い	中程度	激しい
	0	1	2	3
1. 全体的な不快感	☐	☐	☐	☐
2. 疲労感	☐	☐	☐	☐
3. 頭痛	☐	☐	☐	☐
4. 目の疲れ	☐	☐	☐	☐
5. 目の焦点合わせの困難	☐	☐	☐	☐
6.a 唾液の増加	☐	☐	☐	☐
b 唾液の減少	☐	☐	☐	☐
7. 発汗	☐	☐	☐	☐
8. 吐き気	☐	☐	☐	☐
9. 集中することの困難	☐	☐	☐	☐
10. 頭全体の圧迫感	☐	☐	☐	☐
11. 視覚のぼけ	☐	☐	☐	☐
12. dizzy* (目を開けて)	☐	☐	☐	☐
13. dizzy* (目を閉じて)	☐	☐	☐	☐
14. Vertigo**	☐	☐	☐	☐
15. Stomach awareness***	☐	☐	☐	☐
16. げっぷ	☐	☐	☐	☐
17. けん怠感	☐	☐	☐	☐
18. 眠気	☐	☐	☐	☐
19. 精神的な抑うつ	☐	☐	☐	☐
20. Visual flashbacks****	☐	☐	☐	☐
21. 気を失いそうな感じ	☐	☐	☐	☐
22. 呼吸の意識(気になる)	☐	☐	☐	☐
23. 食欲の喪失	☐	☐	☐	☐
24. 食欲の増加	☐	☐	☐	☐
25. 便意	☐	☐	☐	☐
26. 嘔吐 Yes		No		
27. その他.....	☐	☐	☐	☐

*dizzy とは、めまいのうち、立ちくらみに近い感覚(目の前が暗く なる・ 軽い方向失調感、など) のこと
** Vertigo とは、めまいのうち、回転するような感覚のこと
*** Stomach awareness とは普通、吐き気を感じる前の段階に感じる不快感のことを言う
**** Visual flashbacks: 実験中の感覚の後遺症(錯覚的な・ 動いている感覚)

POST

Participant _____ Date_____ Condition_____

実験セッションの終了直前における、あなたの症状について、該当するボックスにチェックしてください。

	症状無	軽い	中程度	激しい
	0	1	2	3
1. 全体的な不快感	☐	☐	☐	☐
2. 疲労感	☐	☐	☐	☐
3. 頭痛	☐	☐	☐	☐
4. 目の疲れ	☐	☐	☐	☐
5. 目の焦点合わせの困難	☐	☐	☐	☐
6.a 唾液の増加	☐	☐	☐	☐
b 唾液の減少	☐	☐	☐	☐
7. 発汗	☐	☐	☐	☐
8. 吐き気	☐	☐	☐	☐
9. 集中することの困難	☐	☐	☐	☐
10. 頭全体の圧迫感	☐	☐	☐	☐
11. 視覚のぼけ	☐	☐	☐	☐
12. dizzy* (目を開けて)	☐	☐	☐	☐
13. dizzy* (目を閉じて)	☐	☐	☐	☐
14. Vertigo**	☐	☐	☐	☐
15. Stomach awareness***	☐	☐	☐	☐
16. げっぷ	☐	☐	☐	☐
17. けん怠感	☐	☐	☐	☐
18. 眠気	☐	☐	☐	☐
19. 精神的な抑うつ	☐	☐	☐	☐
20. Visual flashbacks****	☐	☐	☐	☐
21. 気を失いそうな感じ	☐	☐	☐	☐
22. 呼吸の意識(気になる)	☐	☐	☐	☐
23. 食欲の喪失	☐	☐	☐	☐
24. 食欲の増加	☐	☐	☐	☐
25. 便意	☐	☐	☐	☐
26. 嘔吐 Yes		No		
27. その他.....	☐	☐	☐	☐

*dizzyとは、めまいのうち、立ちくらみに近い感覚(目の前が暗く なる・軽い方向失調感、など) のこと
** Vertigoとは、めまいのうち、回転するような感覚のこと
*** Stomach awarenessとは普通、吐き気を感じる前の段階に感じる不快感のことを言う
**** Visual flashbacks: 実験中の感覚の後遺症(錯覚的な・動いている感覚)

Appendix 25

Motion Sickness Susceptibility Questionnaire (Japanese)

この質問用紙はあなたがどのような類の動きに対して最も不快感を引き起こされるのか、どのくらい影響を受けやすいのかを見つけるために作りました。不快感とはこの場合、吐き気やむかつき、実際に吐いてしまうといった症状のことです。

この質問用紙はいくつかの事前調査の後に、２つのセクションがあります。

セクションAはあなたが子供の頃の乗り物酔いの経験に関するものです。子供の頃とは１２歳以前の頃をさします。

セクションBはあなたの最近１０年間の乗り物酔いの経験に関するものです。

どのようにして質問に答えればよいかは質問表の本文に書いてあります。全ての質問に答えてください。

ご協力よろしくお願いします。

事前調査事項

11. 年齢 _____ 歳

12. 性別（マルで囲む） 男性 女性

13. 現在の職業 _____

14. 自分は乗り物酔いの影響を受けやすいと思いますか。（マルで囲む）

全く受けない　わずかに受ける　中程度に受ける　大変よく受ける

Section A: Your CHILDHOOD experience only (before 12 years of age)
以下のタイプの乗り物や遊具に関して答えてください。

15. 子供の頃（１２歳以前）、何回にわたって以下の乗り物を使った旅行や遊具・設備の使用がありましたか。

	全く無い	1～4回	5～10回	11回以上
車				
バス				
電車				
飛行機				
小型船				
大型船・フェリー				
ブランコ				
ラウンドアバウト				
ジェットコースター				
映画の視聴				
	0	1	2	3

16. 子どもの頃（１２歳以前）、どのくらいの頻度で吐き気や不快感を感じましたか

	全く無い	めったに無い	時々	頻繁に	いつも
車					
バス					
電車					
飛行機					
小型船					
大型船・フェリー					
ブランコ					
ラウンドアバウト					
ジェットコースター					
映画の視聴					
	0	1	2	3	4

17. 子供の頃（１２歳以前）、どのくらいの頻度で吐きましたか

	全く無い	めったに無い	時々	頻繁に	いつも
車					
バス					
電車					
飛行機					
小型船					
大型船・フェリー					
ブランコ					
ラウンドアバウト					
ジェットコースター					
映画の視聴					
	0	1	2	3	4

Section B: Your experience over the last 10 years (approximately).
以下のタイプの乗り物や遊具に関して答えてください。

18. 最近10年間、何回にわたって以下の乗り物を使った旅行や遊具・設備の使用が在りましたか。

	全く無い	1～4回	5～10回	11回以上
車				
バス				
電車				
飛行機				
小型船				
大型船・フェリー				
ブランコ				
ラウンドアバウト				
ジェットコースター				
映画の視聴				
	0	1	2	3

19. 最近10年間、どのくらいの頻度で吐き気や不快感を感じましたか

	全く無い	めったに無い	時々	頻繁に	いつも
車					
バス					
電車					
飛行機					
小型船					
大型船・フェリー					
ブランコ					
ラウンドアバウト					
ジェットコースター					
映画の視聴					
	0	1	2	3	4

20. 最近10年間、どのくらいの頻度で吐きましたか

	全く無い	めったに無い	時々	頻繁に	いつも
車					
バス					
電車					
飛行機					
小型船					
大型船・フェリー					
ブランコ					
ラウンドアバウト					
ジェットコースター					
映画の視聴					
	0	1	2	3	4

Appendix 26

SSQ pre- and post-scores for chapters 3-6

	Table 1. Chapter 3 experiment 1 and 2 SSQ pre- and post- scores									
	Exp. 1								Exp. 2	
Condition	F		B		FB		R		S	
SSQ score	pre	post	pre	post	pre	post	pre	post	pre	post
	6.62	30.61	5.75	29.74	11.51	42.37	10.36	64.73	5.04	19.64

	Table 2. Chapter 4 experiment 1 SSQ pre- and post- scores							
	Exp. 1							
Condition	0.025 Hz		0.05 Hz		0.1 Hz		0.2 Hz	
SSQ score	pre	post	pre	post	pre	post	pre	post
	6.55	24.31	6.23	30.23	5.92	40.52	7.48	42.69
	Table 3. Chapter 4 experiment 2 SSQ pre- and post- scores							
	Exp. 2							
Condition	0.2 Hz		0.4 Hz		0.8 Hz		1.6 Hz	
SSQ score	pre	post	pre	post	pre	post	pre	post
	3.12	25.56	7.17	25.25	4.68	24.93	4.36	25.87

	Table 4. Chapter 5 SSQ pre- and post- scores							
Condition	CF		FE		GS		FV	
SSQ score	pre	post	pre	post	pre	post	pre	post
	5.29	42.39	4.68	52.36	5.29	45.50	6.23	47.99

	Table 5. Chapter 6 SSQ pre- and post- scores					
Condition	R		FB		RFB	
SSQ score	pre	post	pre	post	pre	post
	3.43	35.22	6.23	33.35	7.17	39.27

Appendix 27

Friedman tests for order effects regarding accumulated sickness rating, time to sickness rating 2, and change in total SSQ scores for each of the individual experiments described in chapters 3-6

	Accumulated sickness rating	Time to sickness rating 2	Total change in total SSQ score
Chapter 3	Chi-Square = 1.40, p = .705	Chi-Square = 3.00, p = .392	Chi-Square = 3.27, p = .352
Chapter 4 Exp 1	Chi-Square = 7.78, p = .051	Chi-Square = 5.44, p = .142	Chi-Square = 5.64, p = .131
Chapter 4 Exp 2	Chi-Square = 0.18, p = .981	Chi-Square = 1.04, p = .791	Chi-Square = 0.82, p = .844
Chapter 5	Chi-Square = 4.92, p = .178	Chi-Square = 6.28, p = .099	Chi-Square = 5.87, p = .118
Chapter 6	Chi-Square = 1.16, p = .559	Chi-Square = 0.91, p = .636	Chi-Square = 2.33, p = .311

Appendix 28

Description of visual stimuli employed in the experimental studies presented in chapter 3-6.

Optic flow stimuli simulated the visual motion seen by an observer during sinusoidal linear oscillation in the fore-and-aft (anterior-posterior *or* x) axis. Forward (backward) motion was simulated by outward (inward) moving radial motion. The visual stimuli consisted of a uniformly filled cloud of randomly positioned white dots/objects (n=500) on a black background. The projected motions in the display were geometrically correct projections of rigid motion. Dot velocity and size varied exponentially as a function of their simulated location in depth. Dot size at the eye ranged from 0.22° of visual angle at the middle to 2.97° of visual angle at the periphery. Dots located furthest (nearest) in space had the lowest (highest) peak velocity.

For each of the oscillating optic flow pattern simulating observer motion in the fore-and-aft axis as employed in chapters 3-6 (frequency range: 0.025 – 1.6 Hz), the below table shows (in pixels per second) the (1) average RMS object velocity; (2) RMS value of the object with the minimum RMS velocity; (3) RMS value of the object with the highest RMS velocity; (4) average object peak velocity; (5) peak velocity of the object with the lowest peak velocity (discounting stationary objects); and (6) peak velocity of the object with the highest peak velocity.

Frequency (Hz)	1. Average RMS Velocity (pixels/sec)	2. Min RMS Velocity (pixels/ sec)	3. Max RMS Velocity (pixels/ sec)	4. Average Peak Velocity (pixels/sec)	5. Min Peak Velocity (pixels/sec)	6. Max Peak Velocity (pixels/sec)
0.025	263.25	5.34	2540.65	809.338	27.931	22839
0.05	263.607	5.333	2380.36	886.752	21.107	22839
0.1	264.333	5.433	2417.9	1044.36	18.374	22839
0.2	267.081	7.42	2644.46	1260.32	24.062	22844.4
0.4	247.251	5.863	2644.17	934.776	16.26	22838.5
0.8	267.088	5.558	2954.098	918.109	13.564	22838.1
1.6	262.43	6.903	4733.036	600.146	15.23	22831.8