UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS

Institute of Sound & Vibration Research

Motion sickness with lateral and roll oscillation

by

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ABSTRACT

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MOTION SICKNESS WITH LATERAL AND ROLL OSCILLATION

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Tilting-trains have been developed to provide passengers with shorter journey times by increasing train speeds whilst maintaining passenger comfort. Motion sickness has been reported on tilting-trains and it was suggested that either lateral or roll oscillations are responsible. Previous laboratory studies have shown that motion sickness depends on the magnitude and frequency of oscillation, although few data pertained to either lateral oscillation or oscillation at frequencies less than 0.2 Hz – a frequency range in which tilting-train passengers are exposed. The aim of the thesis was to explore the effects on motion sickness of lateral and roll oscillation with the objective of identifying the effects of oscillation frequency and magnitude when the motions were presented in isolation or in combination.

A pilot investigation found that motion sickness was not significantly different with sinusoidal and octave-band motion waveforms (when having the same oscillation centre-frequency and root-mean-square acceleration magnitude). It was suggested that laboratory investigations of sinusoidal oscillation are relevant to tilting-train motions, which rarely have deterministic oscillations.

The first main experiment investigated pure lateral oscillation at frequencies in the range from 0.0315 to 0.8 Hz. Motion sickness varied significantly with the frequency of oscillation. Using additional data from previous studies, a realisable acceleration frequency-weighting was defined to describe the susceptibility to motion sickness as a function of lateral oscillation frequency. The weighting differed from that previously defined for vertical acceleration and had a gain proportional to acceleration with frequencies less than 0.25 Hz and a gain proportional to velocity at frequencies greater than 0.25 Hz.

A second experiment studied lateral oscillations at frequencies in the range from 0.05 to 0.8 Hz but with roll motion added so as to fully compensate for the lateral forces. When compared to uncompensated lateral oscillations, the addition of fully-compensating roll oscillation tended to increase sickness and the effect was significant with oscillation frequencies in the range from 0.16 to 0.315 Hz. With oscillations in the range from 0.05 to 0.315 Hz, the effect of lateral oscillation frequency on motion sickness with full roll-compensation was similar to that found when no roll was added. A third study investigated the effect on motion sickness of the percentage of roll-compensation when it increased in the range from 0 to 100% with lateral oscillation frequencies at either 0.1 or 0.2 Hz. Significantly more illness was found with higher percentages of roll compensation than with lower percentages. When compared to motion sickness with uncompensated lateral oscillations, there was a trend of less illness with low angles of roll (and therefore low percentages of roll compensation), but significant differences were not consistently observed.

Combined findings from these laboratory studies and an earlier study of pure roll oscillation suggest that motion sickness with lateral and roll oscillations may not be predicted by models with only subject-lateral motion, only Earth-lateral motion, or only roll motion.

A quantitative motion sickness model based on the concept of neural mismatch was derived to predict motion sickness with lateral and roll oscillations. Motion sickness was dependent on the magnitude of the vector difference between the sensed and expected forces, where the expected force was that due to gravity. No frequency-dependent terms were used in the model. When optimised separately for groups of similar conditions, the model predicted the effect of magnitude for the motions studied in each laboratory experiment; however, a unique set of model parameters that could predict all the effects of magnitude was not found. Further consideration of the effect of oscillation frequency was suggested; the model predicted similar frequency-weightings for lateral and vertical oscillations when the resultant force, rather than the stimulus acceleration, was considered.

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ACKNOWLEDGEMENTS

I thank Professor Mike Griffin for providing me with the opportunity to research the phenomenon of motion sickness, for his kind support, and for his patience!

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To Mum, Dad and Ali

DEFINITION OF SYMBOLS

The symbols are listed in groups in the order in which they were defined in the thesis.

Chapter 2 Literature review – Section 2.3 The terrestrial force environment

$\mathbf{a}$	= acceleration vector (m/s²)
a_x	= fore-and-aft acceleration in an Earth-referenced orthogonal coordinate system (m/s²)
a_y	= lateral acceleration in an Earth-referenced orthogonal coordinate system (m/s²)
a_z	= vertical acceleration in an Earth-referenced orthogonal coordinate system (m/s²)
f	= frequency of oscillation, cycles per second (Hz)
$\mathbf{f}$	= non-specific or specific gravito-inertial force vector (N or m/s²)
$\lvert\mathbf{f}\rvert$	= magnitude of the gravito-inertial force vector (N)
$\mathbf{f}_{gravity}$	= generalised force vector due to a gravitational field (N)
$\mathbf{f}_{inertial}$	= inertial force vector arising from acceleration (N)
$\mathbf{f}_{specific}$	= specific force vector (N)
f_x	= fore-and-aft specific[1] force in an Earth-referenced orthogonal coordinate system (m/s²)
f'_x	= fore-and-aft specific force in a coordinate system rotated relative to Earth (m/s²)
f_y	= lateral specific force in an Earth-referenced orthogonal coordinate system (m/s²)
f'_y	= lateral specific force in a coordinate system rotated relative to Earth (m/s²)
f_z	= vertical specific force in an Earth-referenced orthogonal coordinate system (m/s²)
f'_z	= vertical specific force in a coordinate system rotated relative to Earth (m/s²)
g	= magnitude of the specific force due to gravity (m/s²)
$\mathbf{g}$	= specific force or acceleration vector due to gravity (m/s²)
g_y	= lateral component of specific force or acceleration due to gravity (m/s²)
g_z	= vertical component of specific force or acceleration due to gravity (m/s²)
m	= mass of a body (kg)
x	= direction of fore-and-aft axis in an Earth-referenced orthogonal coordinate system
x'	= direction of fore-and-aft axis in an orthogonal coordinate system rotated relative to Earth
y	= direction of lateral axis in an Earth-referenced orthogonal coordinate system
y'	= direction of lateral axis in an orthogonal coordinate system rotated relative to Earth
z	= direction of vertical axis in an Earth-referenced orthogonal coordinate system
z'	= direction of vertical axis in an orthogonal coordinate system rotated relative to Earth
α_f	= roll angle between gravito-inertial force vector and Earth-referenced *z*-axis (°)
β_f	= roll angle between gravito-inertial force vector and subject-referenced *z*-axis (°)
θ	= rotational displacement about the Earth-referenced y-axis (pitch) (°)
φ	= rotational displacement about the Earth-referenced x-axis (roll) (°)
ψ	= rotational displacement about the Earth-referenced z-axis (yaw) (°)

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[1] Specific is used to denote force variables having a 'force per unit mass' such that they have the units of acceleration (m/s²)

Chapter 2 Literature review – Section 2.4 Perception of motion

τ_f = otolith dynamic response time constant (s)

τ_ω = semi-circular canal dynamic response time constant (s)

Chapter 2 Literature review – Section 2.5 Tilting-train motion characteristics

a = magnitude of centripetal acceleration (m/s²)

c_{abs} = absolute compensation ratio between coach-lateral and Earth-lateral forces

c_{rel} = relative compensation ratio between coach-lateral and track-lateral forces

F = centrifugal force (N)

f_{yt} = lateral force in the plane of the track (N)

R = radius of a curve (m)

v = velocity (km/h or m/s)

φ_c = roll of carriage relative to track (°)

φ_t = roll of track relative to Earth (°)

$\ddot{\varphi}$ = rotational acceleration about roll axis (°/s²)

Chapter 3 Low frequency motion in tilting-trains – Section 3.2 Method

$a'_{y,f,rms}$ = octave-band root-mean-square coach-lateral acceleration at centre frequency, f (m/s² r.m.s)

$a_{y,f,rms}$ = octave-band root-mean-square Earth-lateral acceleration at centre frequency, f (m/s² r.m.s)

c = overall compensation ratio

c_f = compensation ratio at each centre-frequency

df = frequency width or resolution between power spectral density points (Hz)

n = Power Spectral Density point index

N = number of octave-band centre frequencies across which a quasi-static approximation applies

$N_{1\,Hz}$ = number of lines in power spectral density in the frequency range below 1 Hz

$P_{xx,n}$ = magnitude of the n-th power spectral density point ([Units]²/Hz)

RMS = root-mean-square value

RMS_f = root-mean-square value at octave-band centre frequency, f

$\dot{\varphi}$ = rotational velocity about roll axis (coach-referenced) (°/s)

Chapter 9 Discussion – Section 9.2 Modelling motion sickness

e = error, or conflict, vector arising from vector difference between sensed and expected forces, with lateral and vertical components, e_y and e_z

$|e|$ = magnitude of the error, or conflict, vector

$|e(t)|$ = magnitude of error, or conflict, as a function of time

e_φ = angular orientation error between orientation of Earth expected from otolith sensation and that sensed by the semi-circular canals

$e_{||}$ = magnitude error between magnitude of resultant force sensed by otoliths and the expected force due to gravity

$\mathbf{f}_{exp}$ = expected force vector

f_{oto} = resultant force vector sensed by otoliths

$\mathbf{f}_{sens}$ = sensed force vector

f_{y0} = amplitude of force during Earth-lateral harmonic oscillation

$f_y(t)$ = Earth-lateral force as a function of time

$f_{y,oto}$ = lateral component of force sensed by otoliths

$f_{z,oto}$ = vertical component of force sensed by otoliths

f_{scc} = resultant force vector expected from semi-circular canal sensation

$f_{y,scc}$ = lateral component of force expected from semi-circular canal sensation

$f_{z,scc}$ = vertical component of force expected from semi-circular canal sensation

$|f_{oto}|$ = magnitude of the resultant force sensed by otoliths

$|f_{scc}|$ = magnitude of the resultant force expected from semi-circular canal sensation

$k_{y,oto}$ = model parameter (coefficient) relating to the sensed subject-lateral force

$k_{y,scc}$ = model parameter (coefficient) relating to the expected subject-lateral force

$k_{z,oto}$ = model parameter (coefficient) relating to the sensed subject-vertical force

$k_{z,scc}$ = model parameter (coefficient) relating to the expected subject-vertical force

p = proportion of compensation (compensation ratio between subject-lateral and Earth-lateral forces)

φ_{oto} = orientation with respect to the Earth determined by otolith sensation

φ_{scc} = orientation with respect to the Earth determined by semi-circular canal sensation

ω = angular frequency of oscillation (radians/s = 2 x π x f)

$\boldsymbol{\omega}_{exp}$ = estimated roll velocity vector

CHAPTER 1 INTRODUCTION

For many centuries motion sickness has afflicted passengers. Indeed, the noun 'nausea', meaning 'a feeling of sickness with an inclination to vomit', has its root in the Greek word for ship, naus. Motion sickness can have a substantially negative effect on the mental and physical well-being of susceptible individuals. Vomiting is perhaps the most unpleasant response to provocative motions, although other undesirable symptoms, such as cold sweating and stomach awareness, are embraced by the motion sickness syndrome.

Car sickness, sea sickness and air sickness are all well known forms of the motion sickness response; however, as detailed in this thesis, each mode of transport provides its own unique pattern of stimulation: vertical accelerations can cause motion sickness on ships and horizontal accelerations can cause motion sickness in road transport. Of concern in the following series of investigations are the causes of the sickness resulting from a recent advance in a relatively old transport technology: motion sickness arising from the adoption of tilting-trains.

Lateral forces, arising from centripetal accelerations, are felt by passengers within a train as it negotiates curves. Roll displacements are used to reduce the lateral force felt by passengers by aligning their vertical axes with the resultant force (arising from the centripetal acceleration and the Earth's gravitational field). Rail transport employs tilt of the track and tilting-trains to generate "roll-compensation" of the lateral forces.

In order to compete with road travel, tilting-trains have been introduced to reduce travel times by increasing the permitted speeds on existing tracks. It is thought that one cost of the increased speeds realised by tilting-trains is a greater incidence of motion sickness; however the relationship between the tilting-train motions and subsequent motion sickness is not known.

Contemporary models of motion sickness hypothesise the existence of sensory conflict arising from discrepancies between the expected and the actual motion sensations. Most of these models have remained descriptive and/or qualitative with only one sensory-conflict model attempting to provide quantitative predictions of motion sickness. No published studies have reported a sensory-conflict model able to predict quantitatively motion sickness with motions in more than one direction.

The aim of this thesis was to investigate the causes of motion sickness on tilting-trains from laboratory studies of the influences of combined lateral and roll oscillation using a horizontal motion simulator. Figure 1.1 shows the linkages between the objectives and the research tasks required to fulfil the aim of this thesis. The research tasks are summarised as follows.

A multi-faceted review of literature (Chapter 2) has summarised the state of the art with respect to recent laboratory studies and models of motion sickness, as well as the types of motion and motion sickness experienced on tilting-trains. The review established what is known about motion sickness and the forces provoking it, and introduced the mechanisms by which humans perceive motion. Existing motion sickness models were reviewed and a sensory-conflict model, based on Stott's postulates (Stott, 1986), was identified as having the potential to predict motion sickness in the tilting-train environment. Combined lateral and roll oscillation was identified as being a possible contributor to motion sickness on tilting-trains.

The typical ranges and magnitudes of lateral and roll oscillations experienced on an experimental tilting-TGV were determined in Chapter 3 and were used to define appropriate motion conditions for study in the laboratory. Chapter 4 described the methods and procedures to be used in the laboratory investigations. In Chapter 5, a pilot study of the effect on motion sickness of motion waveform considered the suitability of using harmonic oscillations in further laboratory studies: the objective was to determine whether results from these studies would be applicable to transport environments where motions are rarely sinusoidal.

A series of laboratory studies was then conducted to investigate the influence on motion sickness of combined lateral and roll oscillation: the effect of frequency of lateral oscillation (Chapter 6); the effect of oscillation frequency with fully roll-compensating lateral oscillation, when the subjects felt no lateral force (Chapter 7); and the effect of the relative magnitude of lateral and roll oscillation at two frequencies (Chapter 8). In these studies, subjects were asked to rate their illness using a subjective illness rating scale throughout the course of each experiment.

A discussion of the experimental findings (Chapter 9) commences with the formulation of a new quantitative sensory-conflict model: the model has its roots in a conceptual model offered by Stott's postulates and describes conflict arising from discrepancies between the sensed and expected magnitude of the gravito-inertial force. Both qualitative and quantitative predictions of motion sickness from the model are compared to the motion sickness reported during the laboratory investigations. Further analyses compare model predictions of motion sickness with vertical and roll motion with the motion sickness reported in previous studies.

The model is shown to predict motion sickness with seated upright subjects undergoing motions where the forces vary in more than one direction. Further work is identified (Chapter 10) as necessary to investigate the effect on motion sickness of the centre of roll and to consider the effect on motion sickness of relative phase of lateral and roll oscillation. The conclusions and contribution to knowledge arising from the thesis are stated in Chapter 11.

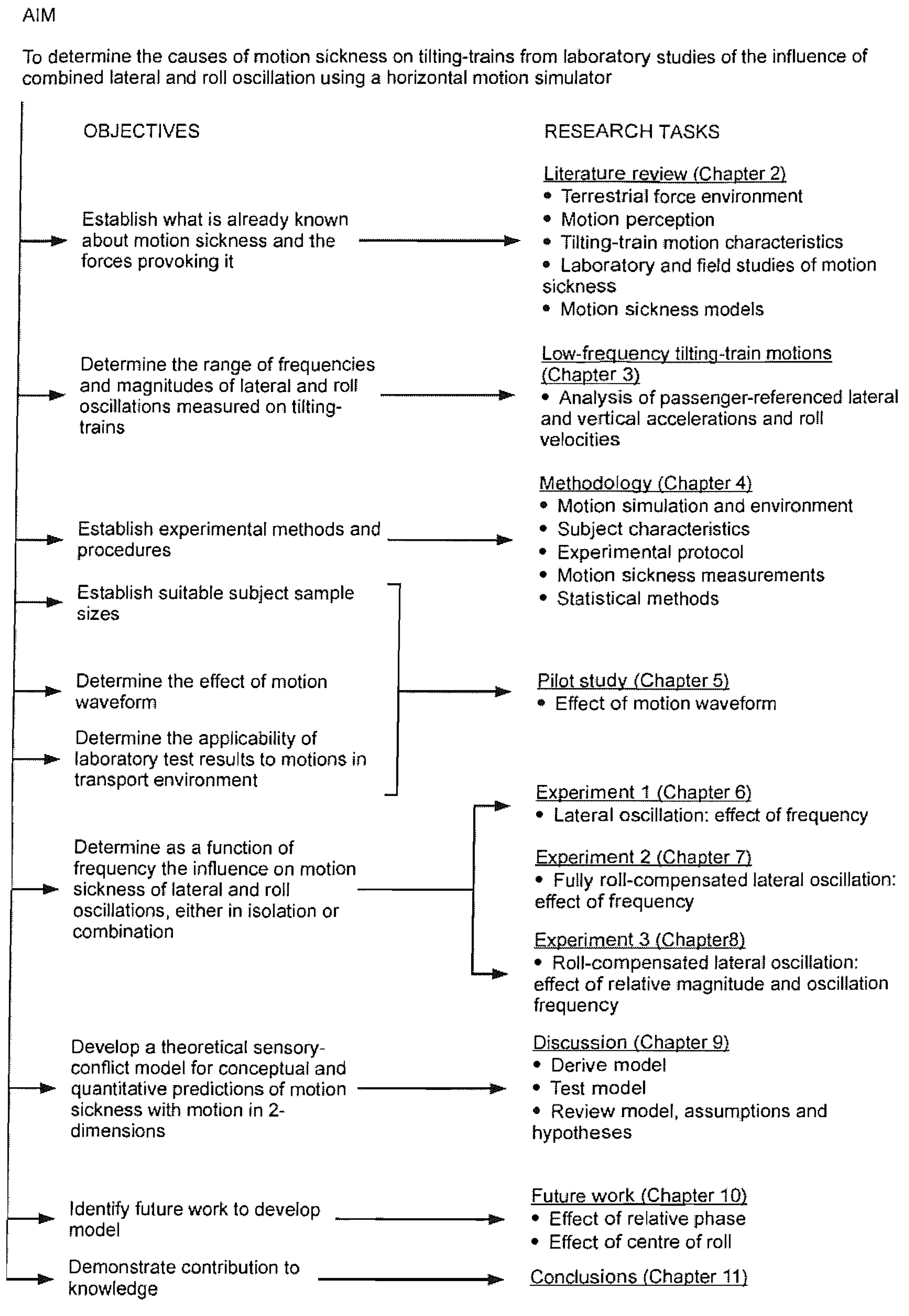

Figure 1.1 Research tasks required to meet the aim and objectives of the thesis.

CHAPTER 2 REVIEW OF LITERATURE

2.1 INTRODUCTION

The review of literature reported here aims to i) establish what is known about the phenomenon of motion sickness and the forces provoking it; ii) introduce the mechanisms by which humans perceive motion; iii) summarise the concepts associated with tilting-train operation; iv) examine existing models of motion sickness and v) identify a model suitable for predicting motion sickness in the tilting-train environment.

2.2 QUANTIFYING MOTION SICKNESS

2.2.1 Introduction

There is no 'gold standard' for the quantification of motion sickness. This section describes briefly signs and symptoms typically associated with the motion sickness syndrome and methods of quantification.

2.2.2 Signs and symptoms associated with motion sickness

Motion sickness is a syndrome such that it is characterised by a collection of signs symptoms. Reason and Brand (Reason and Brand, 1975) categorise the motion sickness response as cardinal signs and symptoms (nausea, vomiting, pallor and cold sweating) and associated reactions (sighing, yawning, headache and drowsiness). The authors suggest that changes in psychological performance and subjective well-being may also be related to the motion sickness phenomenon. Table 2.1 lists signs and symptoms commonly associated with the motion sickness response (Griffin, 1992).

Table 2.1 Signs and symptoms commonly associated with the motion sickness syndrome (Griffin, 1992)

Vomiting	Retching
Nausea	Epigastric symptoms
Colour changes (pallor)	Cold sweating
Irregular breathing (including sighing)	Yawning
Drowsiness	Dizziness
Headaches	

2.2.3 Quantifying motion sickness

Of the signs experienced during motion sickness, vomiting is the easiest to assess objectively: as a dependent variable it is easily observable and unambiguous. For this reason, some researchers have used the vomiting incidence of a population exposed to motion as a measure of motion sickness (e.g. McCauley *et al.*, 1976). However, vomiting may not be the most ethical or practical measure: it may be considered inhumane and may impede the acquisition of future subjects; subjects might not be persuaded to step into an experimental device smelling of vomit, and subjects may not recover quickly, so may not be used in repeated sessions (Reason and Brand, 1975).

Motion end-points derived from symptoms other than vomiting can be used: some investigators have ranked the number, type, and severity of symptoms to form illness rating scales or symptom "checklists" (e.g. Reason and Brand, 1975; Griffin, 1991; Golding & Kerguelen, 1992). In assessing motion sickness severity the subjective interpretation of symptoms may differ for both subject and experimenter. In addition, symptoms may be influenced by factors not related to motion (e.g. health and environment).

2.2.4 Conclusions

For the purposes of this investigation the degree of motion sickness will be assessed using an illness rating scale (derived from Golding & Kerguelen, 1992) and a symptom checklist (derived from Reason and Brand, 1975), both of which are described in Chapter 4 (Section 4.7).

2.3 THE TERRESTIAL FORCE ENVIRONMENT

2.3.1 Introduction

The physical characteristics of the force environment to which humans are normally habituated are reviewed here. The aim is to formalise the definition of the motion stimuli thought to provoke motion sickness. Vector notation is used throughout: vectors are denoted as regular boldface type, whilst scalars are denoted as ordinary italic type; the magnitude of a vector is denoted using parallel vertical bars (e.g. $|\mathbf{a}|$).

2.3.2 Inertial systems and forces

An inertial system is defined as a system with coordinates moving at constant velocity. In an inertial system isolated bodies[2] appear to move uniformly, i.e. at constant velocity or remain at rest, as hypothesised by Newton's first law. The principle of relativity asserts that the laws of physics are the same in all inertial systems.

In a uniformly accelerating system, or 'non-inertial' system, the physical laws become distorted: apparent forces arise due to the acceleration of the co-ordinate system (as opposed to arising from interactions between bodies). These 'inertial', or 'fictitious', forces are proportional to the mass, m, and the acceleration of the system, **a**:

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[2] An isolated body is defined as a mass infinitely far from any other mass such that it is uninfluenced by forces due to gravity or other potential fields.

$$\mathbf{f}_{inertial} \equiv -m \cdot \mathbf{a}$$

Provided the above term is applied to each particle, the laws of physics in a uniformly accelerating system are otherwise identical to those in an inertial system.

2.3.3 Equivalence and gravity

In his principle of equivalence Einstein (Einstein, 1908) expounded an issue arising from the co-existence of non-inertial and gravitational forces (Kleppner & Kolenkow, 1978): there is no way to distinguish locally between a uniform gravitational acceleration **g** and an acceleration of the coordinate system **a** = - **g**. To distinguish between gravity and acceleration an observer in an inertial system must 'look' out of his system to another system that is beyond the influence of the local gravitational field: real fields are local such that at large distances they decrease. An accelerating coordinate system is non-local and the apparent acceleration is observed as uniform throughout space. Only for small systems (such as the terrestrial environment) are the two indistinguishable.

In the terrestrial environment, the gravito-inertial force (**f**) is defined as the vector sum of the gravitational and inertial forces acting on a particle:

$$\mathbf{f} = \mathbf{f}_{gravity} + \mathbf{f}_{inertial}$$

$$\mathbf{f} = m \cdot \mathbf{g} - m \cdot \mathbf{a}$$

$$\mathbf{f} = m \cdot (\mathbf{g} - \mathbf{a})$$

The specific gravito-inertial force is given by normalisation with respect to the mass of the particle on which it is acting, such that it has dimensions of acceleration:

$$\mathbf{f}_{specific} = \mathbf{g} - \mathbf{a}$$

Throughout this thesis all forces will be presented as a specific force ($\mathbf{f} = \mathbf{f}_{specific}$), the force per unit mass, such that they assume the units of acceleration, m/s^2.

Figure 2.1 illustrates the case of a coordinate system undergoing translational acceleration, **a**, relative to an inertial geocentric system. The forces due to inertial motion, $\mathbf{f}_{inertial}$ (= -**a**), the gravity force, **g**, and the gravito-inertial force, **f**, are shown. The magnitudes of the geocentric components of the gravito-inertial force (in this case f_y and f_z) are also indicated.

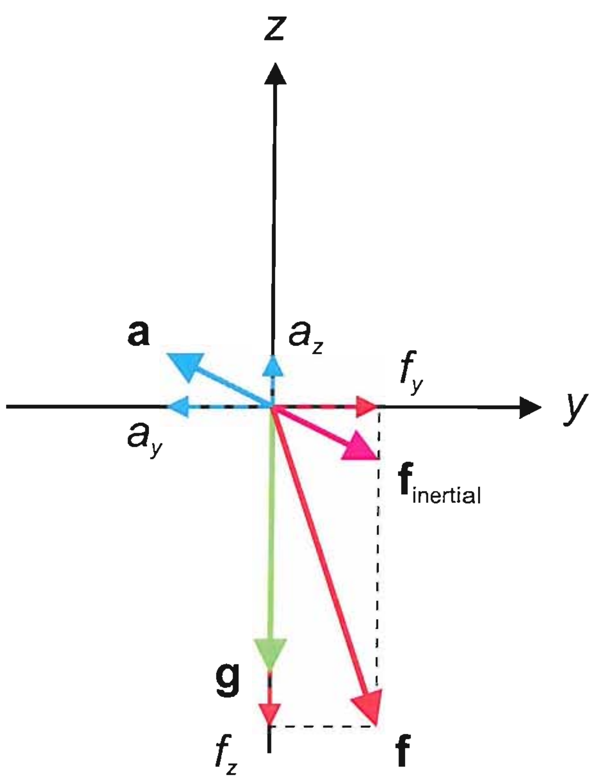
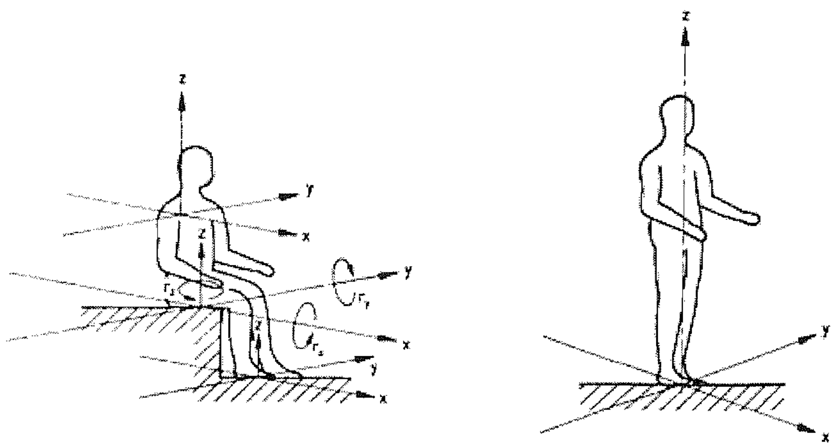


Figure 2.1 A non-inertial coordinate system, aligned with an inertial geocentric system, but undergoing translational acceleration with a direction and magnitude given by **a**. The inertial force observed in the non-inertial reference frame is given by $\mathbf{f}_{inertial}$ and the resulting gravito-inertial force given by **f**.

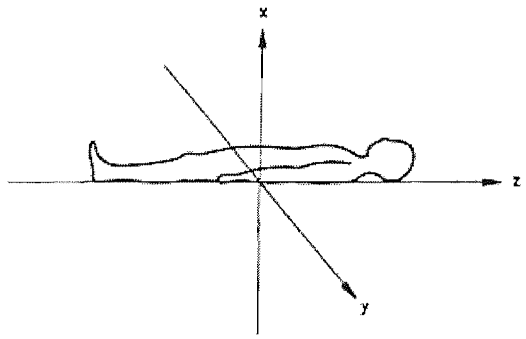
2.3.4 Terrestrial coordinate systems

It is convenient to define the motion of another, inertial or non-inertial, coordinate system relative to an 'inertial' geocentric system. A geocentric coordinate system is defined as an orthogonal coordinate system having its vertical axis aligned, but in a direction opposite, to the force due to gravity (e.g. BS ISO 8727:1997; International Organization for Standardization, 1997a). The horizontal axes then form a plane parallel with the Earth's surface (horizontal plane) and are aligned appropriately for the system of interest. Three assumptions are required to define an 'inertial' geocentric coordinate system: i) the inertial forces due to rotation (see Appendix A) of the Earth are considered negligible relative to the forces due to gravity and inertial motion of the vehicle; ii) the Earth is flat; and iii) the vertical height of the system above the surface of the Earth is small relative to the radius of the Earth such that the force due to gravity is constant (-9.81 m/s²).

A human-referenced, or biodynamic, coordinate system can be defined such that it is fixed relative to the human body (International Organization for Standardization, 1997a). If a biodynamic system accelerates in translation and rotation relative to an inertial geocentric system then the humans will experience inertial forces as described previously (Section 2.3.2).



Basicentric axes for a seated person Basicentric axes for a standing person



Basicentric axes for a prone person

Figure 2.2 Basicentric coordinate systems for a human in seated, standing or prone postures.

A biodynamic coordinate system may originate in anatomical features (e.g. relative to anatomical features of the head; International Organization for Standardization, 1997a); however, in the context of the human response to vibration, biodynamic coordinate systems are typically defined basicentrically (Griffin, 1990). A basicentric system is an orthogonal coordinate system with its origin at a point in or related to a contact surface from which mechanical vibration (or shock) is considered to enter the body. By convention, such systems are right-handed. A common example of a basicentric coordinate system is the system of axes centred on a seat surface at the interfaces with the body. The axes are defined relative to the body and move with the body. Figure 2.2 depicts three common basicentric coordinate systems as defined in the current British Standards relating to the measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock (International Organization for Standardization, 1997b). The basicentric systems are illustrated for seated, standing and prone humans.

2.3.5 <u>The two-dimensional force environment</u>

In two-dimensions the relationships between the forces due to acceleration and gravity are easily defined. Figure 2.1 shows the relationship between acceleration, gravity and the gravito-inertial force for a geocentric two-dimensional coordinate system (in this case defined using *y*- and *z*- axes). In this case the gravity vector is given by

$$\mathbf{g} = \begin{bmatrix} g_y \\ g_z \end{bmatrix} = \begin{bmatrix} 0 \\ g \end{bmatrix}$$

The acceleration vector is given by

$$\mathbf{a} = \begin{bmatrix} a_y \\ a_z \end{bmatrix}$$

The associated expression for the specific gravito-inertial force then follows

$$\begin{bmatrix} f_y \\ f_z \end{bmatrix} = \begin{bmatrix} -a_y \\ g - a_z \end{bmatrix}$$

The gravito-inertial force in a coordinate system rotated by an angle, φ, with respect to the geocentric coordinate system (but otherwise in the same plane) is calculated using

$$\begin{bmatrix} f'_y \\ f'_z \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} f_y \\ f_z \end{bmatrix}$$

$$\begin{bmatrix} f'_y \\ f'_z \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} -a_y \\ g - a_z \end{bmatrix}$$

Figure 2.3 is a vector diagram showing the relationship between the magnitude and direction of a gravito-inertial force with respect to geocentric and rotated reference frames; φ indicates the angle about the *x*-axes of the two systems. A prime is used to distinguish the rotated axes from the geocentric axes. The *y*-axis and *z*-axis components of the gravito-inertial force acting in the two coordinate systems are given by f_y and f_z, and f'_y and f'_z respectively. The direction of the gravito-inertial force with respect to the Earth-vertical axis is given by

$$\alpha_f = \tan\frac{f_y}{f_z}$$

The direction of the gravito-inertial force with respect to the vertical axis of the rotated coordinate system is given by

$$\beta_f = \tan\frac{f'_y}{f'_z}$$

The magnitude of the gravito-inertial force is the same in both the Earth-aligned and rotated coordinate systems, such that

$$|f| = \sqrt{f_y + f_z} = \sqrt{f'_y + f'_z}$$

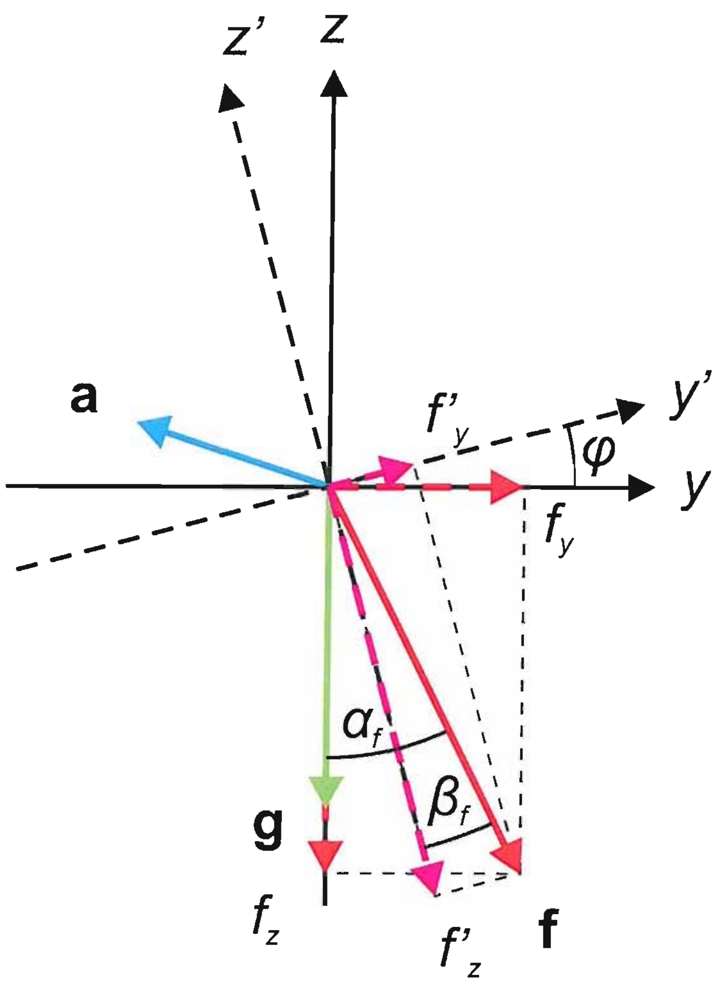


Figure 2.3 Vector diagram showing the relationship between acceleration, **a**, gravity, **g**, and the gravito-inertial force, **f** in a geocentric coordinate system and a coordinate system rotated through an angle, ϕ, about the Earth *x*-axis. A prime is used to distinguish the rotated axes from the Earth-aligned axes. The *y*-axis and *z*-axis components of the gravito-inertial force acting in the Earth-aligned and rotated coordinate system are given by f_y and f_z and f'_y and f'_z respectively. The angles of the gravito-inertial force with respect to the Earth-aligned and the rotated coordinate systems are given by α_f and β_f respectively.

2.3.6 Discussion and conclusions

Inertial forces, arising from translational and rotational accelerations, and the force due to gravity act on a body in an Earth-bound environment. The force environment is characterised by the magnitude and direction of the gravito-inertial force and the orientation (attitude) of a reference frame rotated relative to an inertial geocentric coordinate system aligned with the Earth. The mathematical expressions describing the force environment are simplified by considering a two-dimensional system.

2.4 PERCEPTION OF MOTION

2.4.1 Introduction

The systems responsible for perceptions of motion and self-movement are the ocular system, the vestibular system and the somatosensory system. Respectively, the organs serving these systems are the eyes, the ampullae and maculae, and a combination of the cutaneous, kinaesthetic, and visceral sensory systems. Several theories of motion sickness have been based upon the anatomical and physiological characteristics of the sensory apparatus (see Section 2.8). These systems are described here to facilitate understanding of the motion sickness models described elsewhere.

2.4.2 Anatomy of the peripheral vestibular system

The anatomy of the peripheral vestibular system is shown in Figure 2.4. The vestibular apparatus forms part of the inner ear system and is located within a temporal bone cavity known as the bony labyrinth. Perilymphatic fluids within the bony labyrinth contain the vestibular membranous labyrinths, which in turn contain endolymphatic fluids.

The membranous labyrinths consist of three interconnected semicircular canals and two otolith organs, the utricle and saccule (Hain and Hillman, 1994). To reflect their anatomical arrangement, the orthogonally orientated semi-circular canals are labelled the lateral semicircular canal (lying at about 20° from the horizontal plane), the anterior semicircular canal, and the posterior semicircular canal. The otoliths are arranged such that the saccule is vertical (parasagittal) and the utricle horizontal (close to the plane of the lateral semicircular canals).

The ampullae are the sensory organs of the semicircular canals and are found within a swelling at one end of each canal. The sensory organs of the utricle and saccule are the maculae. The utricular macula is located on its floor and the saccular macula located on its medial wall.

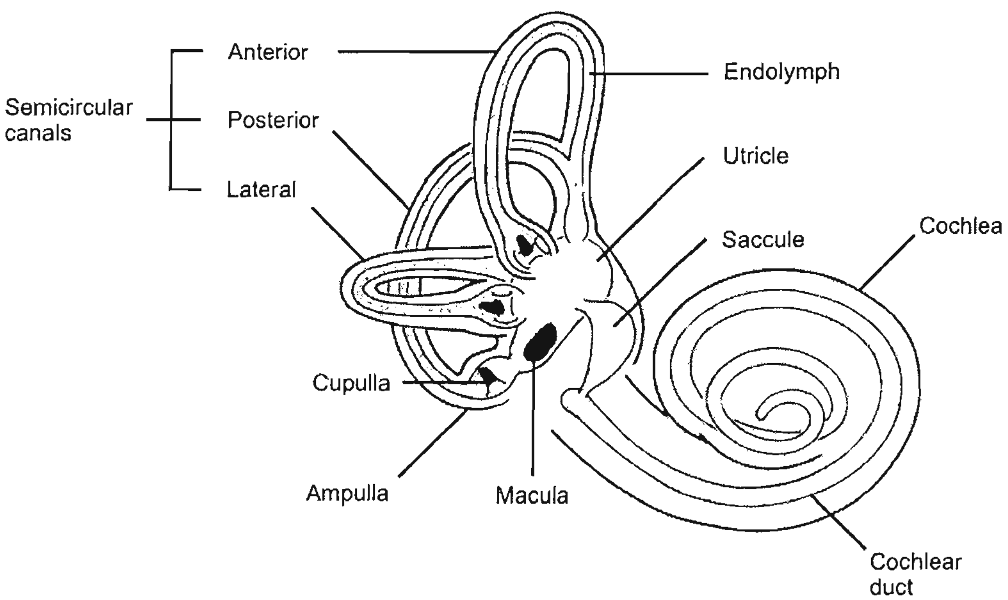


Figure 2.4 Anatomical arrangements of the peripheral vestibular apparatus, indicating the location of the semicircular canals, the otoliths and their respective sensory organs, the ampullae and maculae (adapted from Griffin, 1990).

Specialised hair cells set in to the ampullae and maculae are the biologic sensors that convert hair displacement due to head motion into neural firing. Each hair cell is innervated by an afferent neuron. When hairs are bent toward the longest process of the hair cell, firing rate increases in the neuron and the vestibular nerve is excited (Hain and Hillman, 1994). Conversely, firing rate decreases when the hairs are bent towards the shortest process of the hair cell and the vestibular nerve is inhibited.

The hair cells of the ampullae and maculae are embedded into gelatinous membranes called cupulae and otolithic membranes. The cupula density is equal to that of the surrounding endolymph such that it does not respond to gravity. Statoconia (calcium carbonate crystals) covering the otolithic membrane increase its density relative to the surrounding endolymph causing it to respond to gravity.

The mechanical properties of the coupled endolymph, membrane and hair systems define the fundamental dynamic characteristics of the vestibular apparatus.

2.4.3 Semicircular canal dynamics

During rotation of the head, inertia causes the endolymph to move differentially relative to the canal and the cupula and hairs are deflected in a direction opposite to the head motion (Figure 2.5). Viscous drag arising from the structure of the canals (thin walls; small diameter lumen relative to the radius of the loop curvature) rapidly damps endolymph displacement such that cupula deflection (and neuronal firing rate) is proportional to head angular velocity. The canals therefore function as rate sensors for oscillations in the frequency range 0.05 to 5 Hz (Bos and Bles, 2002).

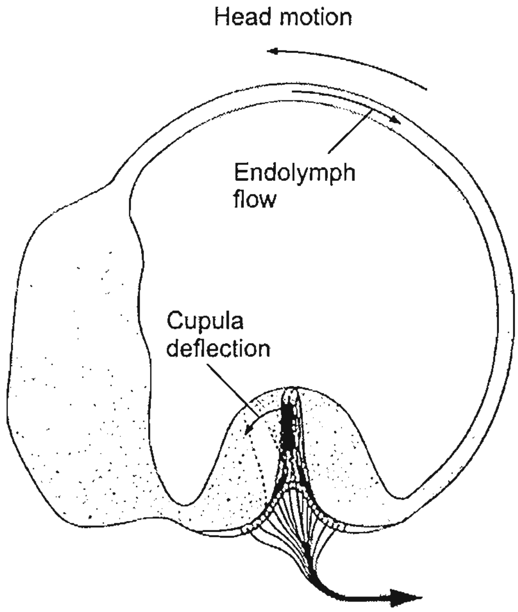


Figure 2.5 Simplified diagram of a semicircular canal illustrating the action of the endolymphatic fluid inertia on the cupula during head rotation (adapted from Webster, 1999).

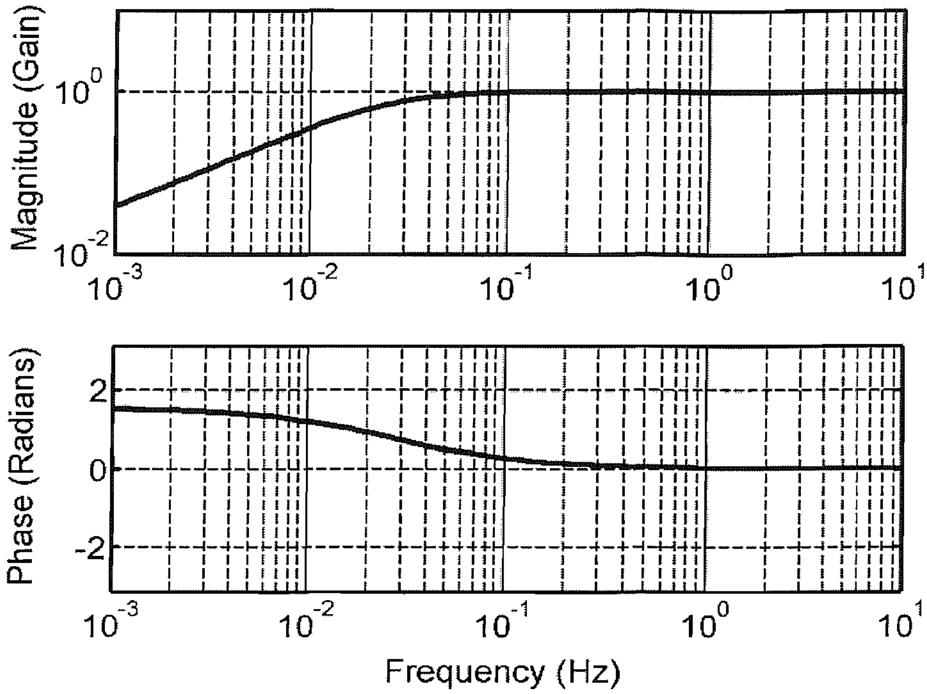


Figure 2.6 Magnitude and phase response of the afferent semicircular canal nerve impulse rate to head angular velocity (derived from Zupan *et al.*, 2002).

In addition to viscous drag, a spring-like restoring force acts within the cupula to return it to its resting position. Thus with constant velocity rotation, the canals only respond as rate sensors for about the first second but their output then decays exponentially with a time constant of about 7 seconds (Hain and Hillman, 1994).

Complex mathematical models of the semicircular canal transfer function describing the neuronal firing rate output in response to angular velocity input have been described elsewhere (Fernandez & Goldberg, 1971; Goldberg and Fernandez, 1971). Recent investigations (Zupan *et al.*, 2002) have suggested that it is sufficient to approximate the semicircular canal response to angular velocity using a transfer function equivalent to a high pass filter (below): the magnitude and phase of the frequency response of the transfer function is shown in Figure 2.6.

$$H(s) = \frac{s \cdot \tau_\omega}{1 + s \cdot \tau_\omega}$$

where the semicircular canal time constant is given by τ_ω (= 6 s).

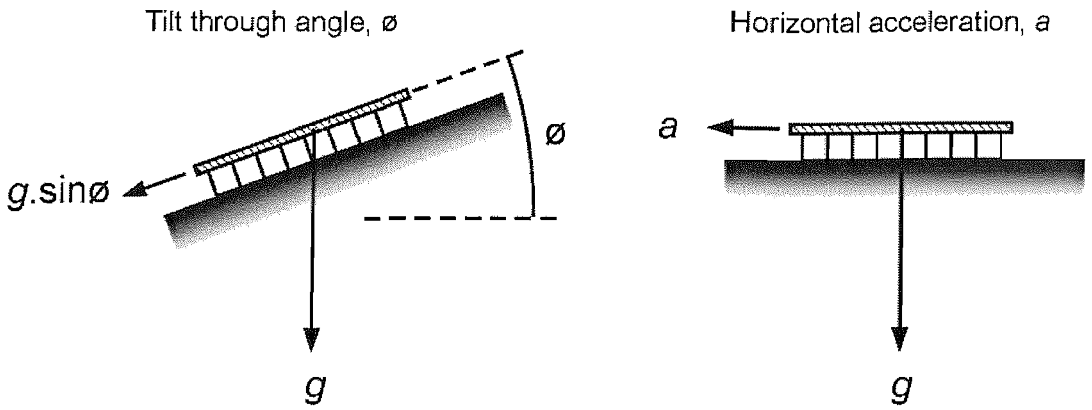


Figure 2.7 Illustration of the equivalent action on the otoliths of the force due to horizontal inertial acceleration, *a*, and a change in orientation with respect to the force due to gravity arising from a tilt, φ (adapted from Griffin, 1990).

2.4.4 Otolith dynamics

By virtue of their increased density relative to the surrounding endolymph, the otolithic membranes of the maculae of the utricle and saccule are sensitive to changes in orientation with respect to gravity and acceleration. The forces due to inertial acceleration and gravity are known to be equivalent (Section 2.3) such that the otoliths are unable to distinguish between the two: equivalent otolithic forces due to acceleration and orientation with respect to gravity are shown in Figure 2.7.

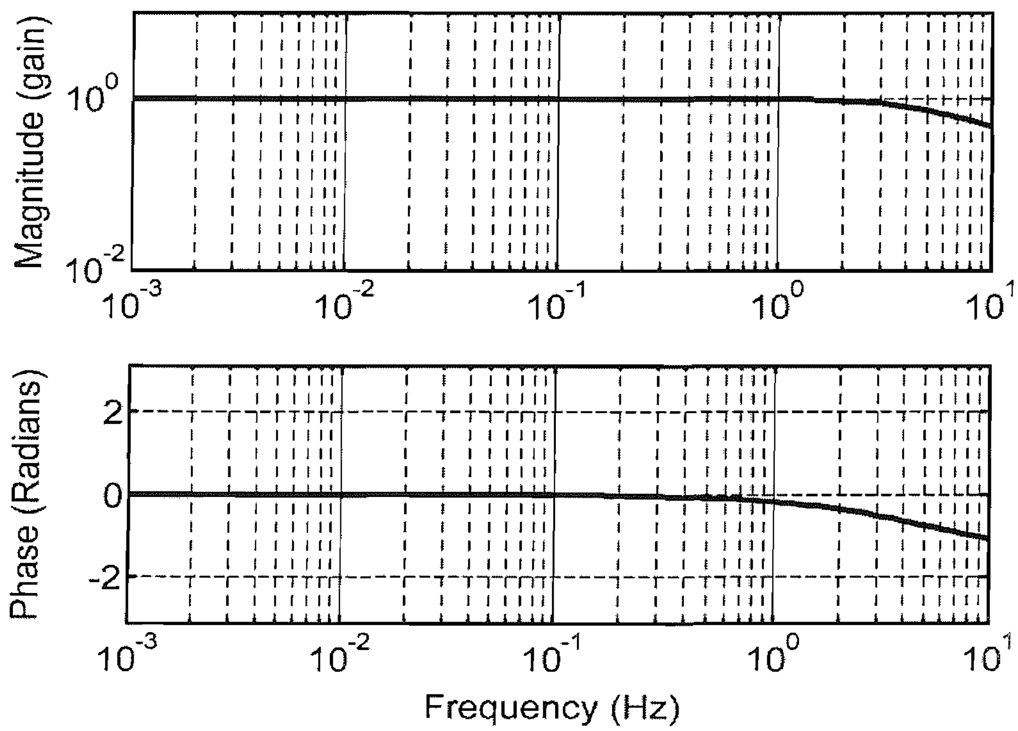


Figure 2.8 Magnitude and phase response of the afferent otolith nerve impulse rate to linear acceleration as represented by first-order transfer function with a time constant of 0.03 s (derived from Young, 1984).

There are only two otoliths for the three axes of linear motion. It is assumed that the sensitive axes are the craniocaudal and anterior-posterior for the saccule, and the interaural and anterior-posterior for the utricle; however, due to the differing hair cell orientations within maculae, the otoliths are multi-dimensionally sensitive (Hain and Hillman, 1994).

The mechanical response of the otoliths to linear acceleration and the force due to gravity can be described as a first-order low-pass filter process: The mechanical otolithic time constant, τ_f, is estimated to be between 0.005 and 0.03 s (Young, 1984). The magnitude and phase of the frequency response of a first-order low-pass filter with a time constant of 0.03 s is shown in Figure 2.8.

$$H(s) = \frac{1}{1 + \tau_f \cdot s}$$

With low frequency oscillations (< 1 Hz) the neural firing response has been approximated as proportional to the gravito-inertial force with a unity gain response in the range 0 – 5 Hz (Bos and Bles, 1998 and 2002). More complex models have defined both a "regular" and an "irregular" response of the otoliths (Zupan *et al.*, 2002): with static tilts, the "regular" (or tonic) response maintains a constant ratio between the firing rate and the applied force, and the firing rate variability is low (Hain and Hillman, 1994; Honrubia and Hoffman, 1993). With sinusoidal translational acceleration, the regular response sensitivity is constant up to 0.1 Hz, but steadily declines at higher frequencies. The "irregular" (or phasic) responses show no firing rate at rest (Hain and Hillman, 1994), but rapidly adapt to constant linear accelerations: they are more sensitive to small changes in linear acceleration, and have a wider frequency response than regular responses (Honrubia and Hoffman, 1993).

2.4.5 Functional involvement of the vestibular system

Introduction

Information from the vestibular system is distributed to several functional systems within the central nervous system. These systems are responsible for maintenance of balance and posture, fixation of vision and emesis. After describing the relevant anatomical and neural structures, the functional relationship of the vestibular system to these systems is described.

Anatomy of the peripheral vestibular nervous system

The neural structures associated with the vestibular system and perceptions of motion are shown in Figure 2.9. The hair cells in the cristae and maculae synapse with the peripheral processes of the vestibular ganglion and form the vestibular division of the vestibulocochlear nerve (the VIIIth cranial nerve). The VIIIth cranial nerve fibres synapse on second order neurones in the vestibular nuclei. The axons of the vestibular nuclei interface the vestibular apparatus and the neural systems known to influence balance, vision, posture, emesis, and conscious awareness of balance (Webster, 1999).

Balance and the cerebellum

The cerebellum is thought to be responsible for motor movements and it uses vestibular information to facilitate coordinated movements that keep the body in balance. The cerebellar cortex receives projections of a complex of axons, originating from some primary nerve fibres (i.e. from the vestibular ganglion) and many second order vestibular central fibres (i.e. from the vestibular nuclei). Furthermore projections from the cerebellum return and synapse on the vestibular nuclei (Webster, 1999).

Vestibulo-ocular reflex

Motor function of the ocular organs is partially controlled by the vestibular system. This facilitates stabilisation of the visual field by attempting to keep the eyes aligned with the geocentric coordinate system using reflexive eye movements directed to compensate for head rotation: the phenomenon is known as the vestibulo-ocular reflex (VOR). Two types of vestibulo-ocular reflex can occur; a response to translational head movement known as the translational (or linear) VOR and a response to rotation of the head denoted the rotational (or angular) VOR (Hain and Hillman, 1994). With humans, the translational VOR is driven by the otoliths and is observed only weakly under conditions of darkness (Hain and Hillman, 1994).

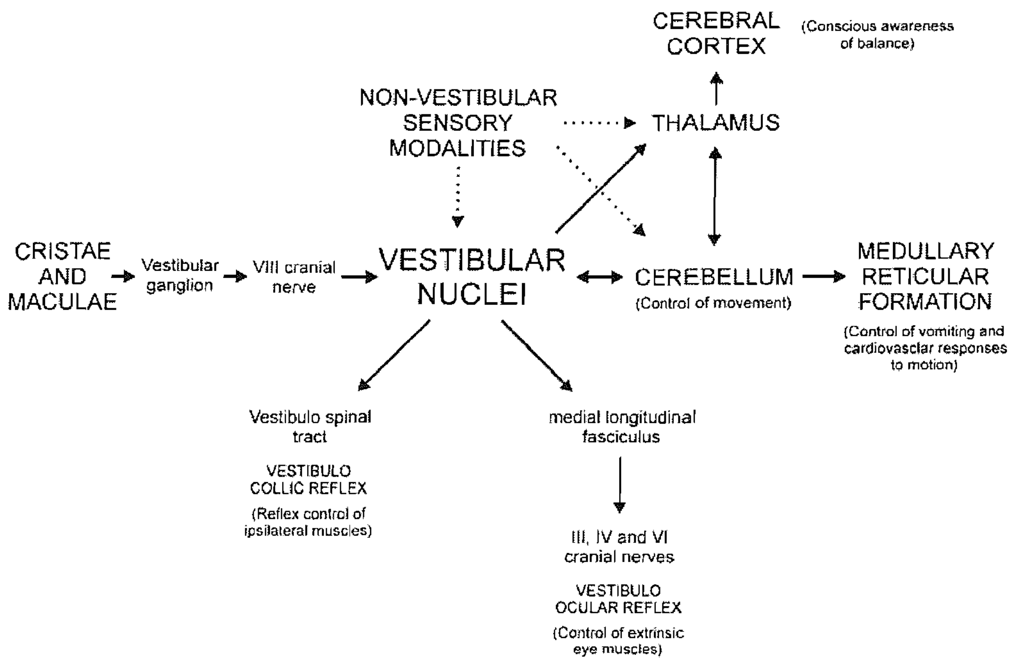


Figure 2.9 Functional arrangement of the vestibular nuclei and the neural systems associated with motion perception, motion control and motion sickness.

The vestibulo-ocular reflex mechanism is mediated by the motor neurones of the extrinsic ocular muscles which synapse with axons projecting from the vestibular nuclei; the vestibular nuclei and the motor nuclei of the IIIrd, IVth, and VIth cranial nerves (oculomotor, trochlear and abducens) are joined bilaterally by the medial longitudinal fasciculus (Webster, 1999).

Postural adjustments (the vestibulo-spinal reflex)

A vestibulo-spinal reflex stimulates postural adjustments in order to maintain posture and to keep humans upright. Here, ipsilateral connections from the lateral vestibular nucleus synapse lower motor neurones via the lateral vestibulo-spinal tract. The lower motor neurones axons extend to the extensor muscles of the arms and legs. It is thought that the response is driven by the otolith organs (Webster, 1999).

Emetic centres

Collaterals of some axons of the vestibular nuclei arrive at an area of the brainstem called the area postrema, which is thought to be an emetic centre. A further neural region in the medulla, distinct from the area postrema, is also thought to contribute as part of the functional vomiting circuit (Crampton, 1990).

2.4.6 Visual perception of motion

The visual system has mechanisms specifically suited for analysing motion and human observers can recover three-dimensional motion trajectories, relative distance, and shape information, from visual motion (Heeger and Simoncelli, 1994). The first stage of motion perception is generally believed to be the measurement of optical flow. Optical flow is a field of two-dimensional velocity vectors, indicating the speed and direction of motion for each small region of the visual field (Heeger and Simoncelli, 1994). The visual system is not a necessary requirement for motion sickness (Griffin, 1990), although it can be a sufficient stimulus (Webb and Griffin, 2002 and 2003). It appears that the visual environment may be used to modify the interpretation of motion perceived via other sensory systems (Griffin, 1990).

2.4.7 Somatosensory perception of motion

A sense of body movement or applied force is given by end organs, distributed throughout the muscles. Together these receptors provide information about limb position, movement, and load (Nicholls *et al.*, 1992): muscle spindle stretch receptors provide information about muscle length, whereas Golgi tendon organs in the muscle tendons signal muscle tension. In addition, a third receptor provides information about joint position.

A variety of receptors in the glabrous skin and deep tissue convey information about touch, pressure and vibration. These receptors (Meissner's corpuscles, Merkel's disks, Ruffini endings and Pacinian corpuscles) are distributed non-uniformly over the body (Nicholls *et al.*, 1992).

A topographic representation of the body surface is maintained throughout the central pathways; in the cortex this representation is highly distorted, in accordance with the density of innervation; e.g. in humans, areas within the central nervous system concerned with hands or fingers are larger than those concerned with the trunk or legs. At each successive level throughout the pathway there is an orderly map of the body correlated with the modalities of touch, pressure and joint position (Nicholls *et al.*, 1992). In some areas of the cortex, neurons with more complex properties have been found; such neurons are driven only by movements involving several joints, for example movement of the entire limb in one direction only (Nicholls *et al.*, 1992). The way in which the brain synthesises information from diverse areas into a complete body image remains elusive (Nicholls *et al.*, 1992). Consequently, the way in which somatosensory information is involved in the causation of motion sickness is unknown.

2.4.8 Discussion and conclusions

By definition, motion sickness must be mediated by the mechanisms responsible for motion perception, be it the otoliths, the semicircular canals, the eyes, or any of the somatosensory systems. This section has identified the motion quantities to which the various sensory systems respond, and, to a varying extent the transduction behaviour of the various systems. Possible motion variables are gravito-inertial forces (e.g. as transduced by the otolith organs), angular velocities, as sensed by semicircular canals and the degree of optic flow (e.g. as transduced by the visual system). Therefore, these quantities are also possible independent variables in subsequent motion sickness experiments. The functional involvement in motion sickness of motion sensory systems is not well known: it has been reported that the vestibular system is critical in the generation of motion sickness (see Section 2.8.2), but it is not clear how visual and somatosensory information affect motion sickness, whether in isolation or after integration with vestibular information. Further experimental investigations of the influence of perceived motion variables are necessary to determine the exact roles of these systems.

2.5 TILTING-TRAIN MOTION CHARACTERISTICS

2.5.1 Introduction

This section aims to describe: i) the origin of the forces experienced during rail travel; ii) the conventional techniques and limitations of counteracting the effects of these forces; and iii) the typical behaviour of the motion characteristics of tilting-trains.

2.5.2 Curvilinear motion

When a particle follows a curved trajectory through space with a velocity, *v,* it experiences an acceleration, *a*, directed along the inward pointing instantaneous radius, *R* (Harris *et al.*, 1998). For circular motion this acceleration is known as centripetal acceleration. To generate this motion, a force, *F*, having a magnitude proportional to the acceleration must be acting on the particle. The force and acceleration magnitudes are proportional to the curve radius and velocity:

$$F \propto a = \frac{v^2}{R}$$

In the case of a train, such an inward force would be generated by a longitudinal reaction at the outer rail as the train rounds a bend in the track.

2.5.3 Reduction of the effects of the forces due to curvilinear motion

Within a train, the acceleration due to curvilinear motion is manifest as a lateral force. Passengers exposed to large lateral forces experience discomfort and it is necessary to reduce the lateral forces in trains to reduce discomfort.

For a given curve, of radius *R*, the lateral force in the cabin-fixed reference frame, f'_y can be reduced by decreasing the train speed, *v*, or by imparting a roll displacement, φ, of the cabin relative to the Earth-horizontal: under quasi-static conditions the change in orientation causes a component of the force due to the Earth's gravitational field, *mg*, to reduce the lateral force in the cabin-fixed reference frame, such that

$$f'_y = f_y \cdot \cos\varphi - m \cdot g \cdot \sin\varphi$$
$$f'_y = m \cdot \left(\frac{v^2}{R} \cdot \cos\varphi - g \cdot \sin\varphi \right)$$

2.5.4 Conventional track design and rationale for tilting-trains

In reality the reduction of lateral forces in trains is achieved by a compromise between reductions in speed and the addition of appropriate roll: reducing speed increases journey time while banking the track too much can cause problems for low-speed traffic (freight) and trains that stop on curves (Harris *et al.*, 1998).

Conventionally, rail systems have achieved the necessary roll by an appropriate rotation of the plane of the track, known as cant. For a given cant and radius of track there is a speed at which the lateral force felt in the plane of the track is zero. This speed is known as the equilibrium speed and at this speed the lateral force on the outer rail (the force perpendicular to the rail length and rail surface) is also zero. The equilibrium speed is the same for all vehicles. If a vehicle traverses the curve at a speed greater than the equilibrium speed lateral forces are experienced. This condition is known as cant deficiency. Cant excess occurs when lateral forces are experienced because a train moves too slowly through a canted curve.

On mixed traffic lines where the track has to be suitable for fast passenger and slow freight trains there is a need to compromise on the ideal cant. The upper limit of cant is determined by several factors: vehicles should be able to stop on curves without too much passenger discomfort from cant excess. A vehicle should not become likely to derail from the lateral forces acting on the inner rail when accelerating from stationary in a curve. The lower limit of cant is determined by the interaction between the track, vehicle and passenger comfort: cant deficiency should not by itself cause unacceptable discomfort and should not cause the train suspension to reach its limits such that passenger discomfort is further increased. Typically, cant deficiency for a conventional non-tilting vehicle must be limited by reduced curve speed. For these reasons mixed traffic track cant tends to be limited within a band around 4 – 6° (Harris *et al.* 1998).

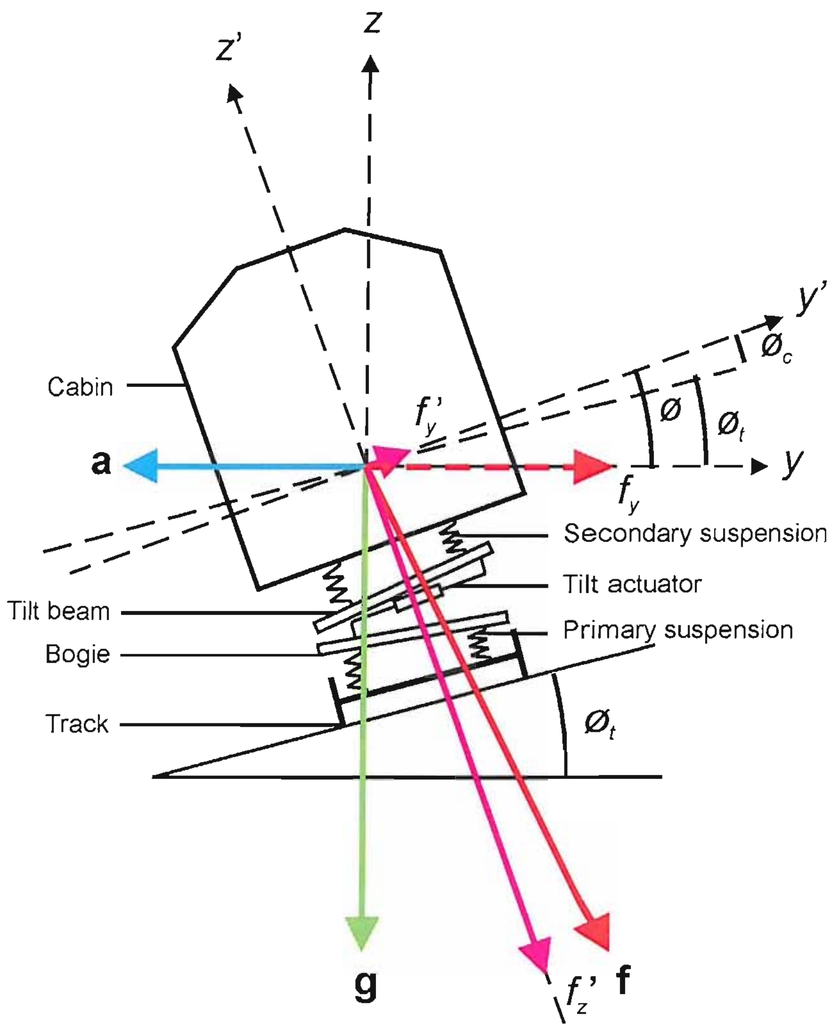


Figure 2.10 Diagram of an actively tilting train during quasi-static cornering conditions.

Tilting-trains have been developed to negate the compromises in speed and cant deficiency associated with conventional trains as they round a curve. As shown in Figure 2.10, active tilt systems use hydraulic or electrodynamic actuators to force a roll displacement of a tilting-train cabin relative to the bogie thereby increasing the effective cant felt by passengers: this has the potential effect of actively maintaining the vehicle floor normal to the direction of the gravito-inertial force vector (Harris *et al.*, 1998).

The total roll of the carriage is given by the sum of the cant due to the track, φ_t, and the roll of the cabin relative to the bogie[3], φ_c:

$$\varphi = \varphi_t + \varphi_c$$

The resultant lateral force measured in the cabin-fixed reference frame can be expressed as a proportion, or percentage, of the lateral force measured in either the Earth-fixed or the track-fixed (denoted f_{yt}) reference frames; the former ratio is defined as the absolute compensation and the latter as the relative, or effective, compensation.

The absolute compensation ratio, c_{abs}, is given by

$$c_{abs} = \frac{f_y - f'_y}{f_y} = 1 - \frac{f'_y}{f_y}$$

The relative or effective compensation ratio is given by

$$c_{rel} = \frac{f_{yt} - f'_y}{f_{yt}} = 1 - \frac{f'_y}{f_{yt}}$$

Neither, the roll displacement of the cabin from the Earth-horizontal, φ, nor the Earth-horizontal acceleration, a_y, is measured in the field. Instead, the force at the track or bogie level is measured so rail engineers tend to quote the performance of the tilt in terms of the relative compensation ratio.

2.5.5 Measurements of tilting-train motion

There is little published information regarding the range of magnitudes and combinations of low-frequency (< 1.0 Hz) lateral and roll motions experienced in tilting-trains. Figure 2.11 shows estimates of acceleration power spectral density calculated in a study of motions onboard an experimental tilting TGV train (Paddan and Griffin, 1999); at low frequencies (< 0.5 Hz), vertical accelerations and fore-and-aft accelerations are small relative to the lateral acceleration. These accelerations have been measured in a vehicle-fixed reference frame and thus were influenced by both inertial and gravitational forces;

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[3] The bogie is assumed rigid such that relative to the Earth-horizontal it has the same cant as the track.

therefore relative to a conventional train and given equivalent curves and speeds, the vertical acceleration in the cabin-fixed reference frame of a roll-compensating tilting-train will be greater than for a conventional train.

2.5.6 Discussion and conclusions

An initial investigation suggests that, at low frequencies (< 1.0 Hz) the dominant motions in tilting-trains are the lateral forces and roll displacements experienced during curves. The extent to which these motions affect motion sickness is not known. The present investigation might usefully be limited to two translational directions, such that the lateral and vertical axes are of interest, and, in addition, the influence of roll by itself and in combination with these motions. More detailed analysis of measured accelerations will be required to define the precise motions of interest.

2.6 STUDIES OF MOTION SICKNESS IN RAIL VEHICLES

2.6.1 Motion sickness in conventional trains

After failing in a "review of the medical literature... to disclose any pertinent studies referring specifically to motion sickness during train travel", Kaplan (Kaplan, 1964) compiled a questionnaire study of 371,261 passengers for the Baltimore and Ohio Railroad Company. The survey sought to establish the incidence of sickness amongst passengers and the possible influences of gender, age, time of onset after entraining, journey topography, diurnal and seasonal variations, and anti-emetic drugs. Motion sickness was evaluated at 2-hour intervals on six trains undertaking a 16-hour journey between Chicago and Baltimore and two trains undertaking a 21-hour journey between Baltimore and St. Louis. Without defining how motion sickness was quantified, the authors reported that over all journeys the average motion sickness incidence was 0.13% (Kaplan, 1964). Females were estimated to be at least three times more likely to report illness than males; although the effect of the variables influencing motion sickness during the study is unclear as no confidence intervals were given.

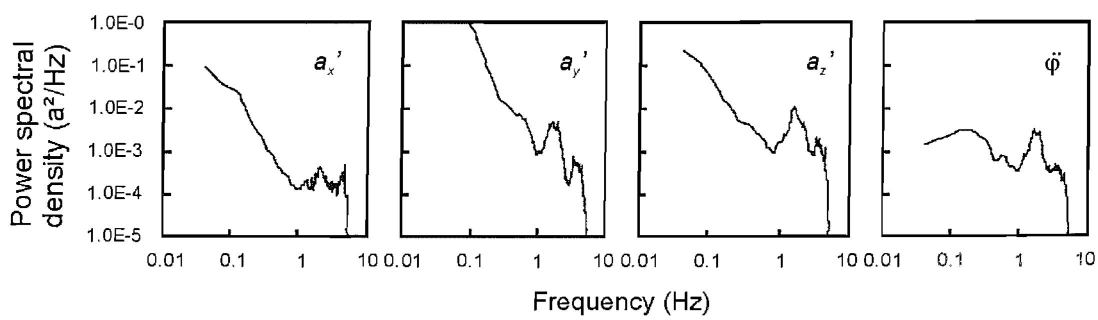

Figure 2.11 Acceleration power spectral density estimates for fore-and-aft (x), lateral (y), vertical (z), and roll (φ – second derivative indicated by double dots) axes. Measurements taken from an experimental tilting train: SNCF - TGV P01 (Paddan and Griffin, 1999). Resolution = 0.039 Hz.

The accelerations in the trains were recorded and the authors surmised that translational acceleration associated with some angular motion of the head appeared to be the prime cause of motion sickness in trains. Additionally the effect of rough terrain (mountains) on motion sickness only appeared significant in daylight hours; generally a diurnal variation was observed with a sharp decrease in illness incidence during the sleeping hours. The authors attributed the cause of increased sickness with increased daylight travel to be the extra number of meals eaten aboard the train. Of the passengers, those that became ill tended to do so within the first four hours of their journey, with a marked decrease in illness toward the end of the trip regardless of the duration of the trip. The authors stated that the low sickness incidence reported was consistent with the public perception of the reduced nauseougenic potential of conventional trains. Anecdotal evidence has proposed that tilting trains, however, have significant nauseogenic potential (Ford, 1990; Ford, 1998).

2.6.2 Motion sickness in passively tilting trains

The Japanese introduced passively tilting-trains (High Curve Speed Railway Vehicle, HCSRV) into service in 1973. The cabin in these trains had a pivot about its longitudinal (fore-and-aft) axis, above the centre of gravity of the cabin; with this arrangement the cabin would swing (roll) inwards due to the centrifugal force as it rounded a curve. The lateral force felt by the passengers was then reduced. Ueno *et al.* (Ueno *et al.*, 1986) used self-administered questionnaires to compare motion sickness in two matched (age, gender, experience) groups of 119 passengers and 100 conductors who had been riding on either a HCSRV or a control train for over two hours. A greater incidence of passengers (31% compared to 5%) and conductors (32% compared to 10%) reported subjective symptoms of nausea in the HCSRV than the control train.

To evaluate the physical characteristics of the roll due to the swing motion of the train, the authors measured the horizontal acceleration on the floor of the cabin[4] using translational accelerometers (with a minimum frequency response of 0.1 Hz). The FFT method was used to calculate the frequency content of the horizontal acceleration in the range 0 to 5.1 Hz. The analysis illustrated that the peak accelerations lay in the range 0.5 - 1 Hz for the HCSRV and above 1 Hz for the control trains. According to Ueno *et al.* these results indicated that motion sickness caused by HCSRVs was due to swing oscillations at frequencies below 1 Hz.

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[4] The authors did not explicitly state that they measured the lateral acceleration, however, since they noted a strong influence of roll displacement on the horizontal acceleration it is inferred that they were referring to the lateral acceleration.

Table 2.2 Tilt-compensation conditions studied on the X2000 tilting-train in Sweden (Förstberg *et al.*, 1996).

Strategy	Speed increase relative to conventional train (%)	Roll compensation (%)	Roll velocity limit (°/s)	Roll acceleration limit (°/s^2)	Resultant lateral acceleration (m/s^2)
A	+ 30	70	4	None	0.6
B	+ 30	40	4	None	1.0
C	+ 10	0	0	0	1.15
D	+ 30	70	2	None	0.7
F	+ 30	55	4	4	0.8
G	+ 30	55	2.3	None	0.8

2.6.3 Motion sickness in actively tilting trains

After development of the X15 prototype tilting-train through the early 1970s, in 1990, Sweden introduced into service its first tilting-train, the X2000. To establish the causes of motion sickness on tilting trains Förstberg (Förstberg *et al.*, 1996) investigated the influence of various active tilt-compensation strategies on an X2000 running over 180 km of curvaceous track between Linköping and Järna (route: Linköping – Norrköping – Flen – Järna). Permitted speeds for this track were 140 – 160 km/h for conventional trains and 180 – 200 km/h for the X2000 tilting-train. More than 200 volunteers, with a higher than average sensitivity to motion sickness, were employed over three separate experiments. All subjects were exposed to at least one return journey with approximate 3-hour duration. Table 2.2 details the range of tilt-compensation conditions studied (speed, compensation, roll velocity limit and roll acceleration limit).

The subject composition, journey departure and destination locations, and compensation conditions studied in each of the three experiments are shown in Table 2.3: in Experiment 1, 61 subjects were divided into three cars for the outbound journey and on the return journey the subjects in car number three were split and moved into cars one and two. Each car used a different tilt-compensation strategy for the duration of the experiment. Experiment 2 divided the 79 subjects into two approximately equal groups; each group was split over two cars with each car having a different tilt-compensation strategy. Each group was exposed to one return journey on each of the two consecutive days. In Experiment 3 the group of 72 subjects was split into three cars, with each having a different tilt-compensation strategy, and was exposed to one return journey on each of three consecutive days. Due to timetabling complexities the return journeys were not all of the same distance for all the experiments.

Table 2.3 Subject composition, test departure and destination locations (L = Linköping, N = Norrköping, F = Flen, J = Järna), passenger grouping, and compensation conditions studied during three experiments in a Swedish X2000 actively tilting-train.

Experiment	1		2					3		
Source of subjects	Adtranz and SJ employees, and KTH students		Linköping University students					Linköping University students		
Total number of subjects	61		79					72		
Average age [range] (Years)	34 [19-65]		26 [19-59]					25 [16-67]		
Ratio (female:male)	20:41		34:45					34:38		
Day	1		1		2			1	2	3
Subject group	1		1	2	1	2		1	1	1
Journey	J-N	N-J	L-J-L	L-F-L	L-J-L	L-J	J-L	L-J-L	L-J-L	L-J-L
Car #1	B	B	A	A	B	C	A	A	F	G
Car #2	D	D	B	D	AB	C	D	G	A	F
Car #3	A	B/D	-	-	-	-	-	-	-	-
Car #4	-	-	-	-	-	-	-	F	G	A

In all three experiments subjects assessed their illness at approximately 45-minute intervals. After completion of the tests, a "symptoms of motion sickness incidence" (SMSI) score was calculated from the number of subjects reporting dizziness, nausea or not feeling well given the condition that the subject had reported "feeling well" at the start of the experiment (Förstberg, 1996). The SMSI was calculated for each of the conditions studied in experiments 1, 2 and 3 and is shown in Table 2.4.

Although the train speeds were not equivalent, Förstberg found that tilt strategy A, with 70% roll compensation, produced significantly ($p < 0.05$) more sickness than tilt strategy C, which used no compensation. The resultant lateral acceleration was less in condition A than in condition C, thus with these conditions illness did not appear to be directly proportional to the resultant lateral acceleration.

Comparing conditions C, with no tilt, and D, with 70% compensation and limited roll velocity, shows that the tilting condition caused more illness than the no-tilt condition, although the difference was not statistically significantly different.

Table 2.4 Percentage of symptoms of motion sickness incidence (SMSI) for each condition in each experiment (Förstberg, 1996).

Experiment	Condition	SMSI (%)
1 and 2	A	19
	B	12
	C	5
	D	19
3	A	14.5
	F	10.7
	G	8.5

Condition B, with 40% compensation, and condition C, with no compensation, had different speeds but similar resultant levels of lateral acceleration, however there was about 50% less illness with no tilt than with tilt, although the difference was not statistically significant. Conditions A and D involved similar speeds and 70% compensation but condition D had a lower roll velocity limit resulting in a greater lateral accelerations. However, this strategy did not cause a statistically significant difference in illness.

In Experiment 3, a comparison of condition A, with 70% compensation, and conditions F and G, both with 55% compensation but with equivalent and lower roll velocity limits respectively, found that condition A produced significantly more motion sickness symptoms. Conditions F and G, both with 55% compensation and similar resultant lateral accelerations but different roll velocity and roll acceleration limits, did not produce significantly different illness.

For conditions A, F and G, Förstberg (Förstberg *et al.*, 1998) evaluated the W_f frequency weighted vertical, lateral and roll accelerations using the motion sickness dose value procedure (see Section 2.10.3). As lateral, vertical and roll motions are covariant in tilting-trains, regression analysis cannot easily be used to test models with more than one of these motion variables. Förstberg noted that it was difficult to separate their combined influence, but, for the tests and analyses performed, the roll acceleration motion dose was the most highly correlated with motion sickness.

In summary, the results are consistent with the conclusion that conventional trains provoke lower rates of illness than tilting-trains. Increasing roll-compensation of lateral acceleration increased the incidence of motion sickness symptoms amongst passengers, but illness did not appear to be simply proportional to either the resultant lateral acceleration or the roll velocity.

Table 2.5 Typical maximum motion values for five conditions investigating various compensation strategies and cant deficiencies (Förstberg, 2003).

Condition	a_y track	Cant deficiency	Effect tilt compensation	Tilt angle	Tilt angle velocity	Roll velocity	a_y coach
	m/s²	mm	%	°	°/s	°/s	m/s²
I	1.8	280	53	4.7	2.35	5.2	1.0
II	1.8	280	45	5.6	2.8	5.7	0.85
III	1.4	220	53	4.7	2.1	4.8	0.7
IV	1.4	220	62	5.4	4.5	5.1	0.6
V	1.0	150	0	0	0	2.1	1.0

Passengers have been travelling on Norway's BM73 class tilting train since November 1999. Immediately prior to the train entering service, Förstberg (Förstberg, 2003) conducted field tests to examine how motion sickness changed with changing tilt strategy. A total of five different combinations of tilt strategy and vehicle speed were investigated. Typical maximum values of the lateral acceleration and roll parameters experienced in each condition are given in Table 2.5. Increases in track lateral acceleration were achieved through increases in the vehicle speed. Between 32 and 60 subjects participated in each return journey, with all but two of the two-hour return journeys occurring on separate days. Subjects rated their motion sickness using a 5-point nausea rating scale; 0: no symptoms; 1: slight symptoms but no nausea; 2: slight nausea; 3: moderate nausea; 4: strong nausea. The mean nausea ratings are shown for each condition in Figure 2.12. With the highest train speed, nausea ratings increased with increasing roll-compensation. With constant roll-compensation, nausea ratings increased with increasing lateral acceleration in the track plane. After further analysis, Förstberg again concluded that the roll acceleration dose was an appropriate predictor of motion sickness.

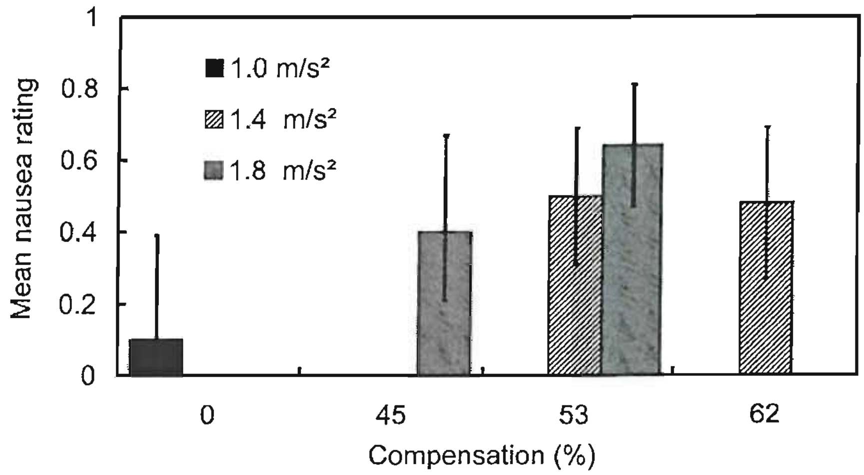

Figure 2.12 Mean nausea ratings as a function of percentage roll-compensation and track lateral acceleration magnitude (Förstberg, 2003).

A Japanese survey of motion sickness reported by 3967 passengers in 14 types of train (8 of which were tilting-trains) sought to investigate the influence of motion frequency and axis (Suzuki and Shiroto, 2003). During a 30-minute period of their journey, passengers were asked to rate their motion sickness using a questionnaire whilst fore-and-aft, lateral and vertical accelerations were measured simultaneously in the coach. The authors used correlation analysis to compare reports of the illness rating "I felt absolutely dreadful" to various weighted acceleration values calculated for each coach-referenced axis of motion: the acceleration data were band-pass filtered (-20 dB/octave roll-off) at one of ten centre frequencies spaced at one-third octave intervals across the frequency range 0.063 to 0.8 Hz. The measurement value of the acceleration magnitude was unspecified; i.e. it was not stated whether the peak, the root-mean-square, or some other acceleration measure was used. From their correlation analysis, the authors concluded that motion sickness rates were higher in tilting-trains than in conventional non-tilting trains and that low frequency lateral oscillation in the range 0.25 to 0.32 Hz highly influenced motion sickness, the greatest correlations having been found between these motions and motion sickness. A separate correlation of motion sickness rates with various single measures of roll motion (mean, maximum, 95^{th} percentile, 30-minute integral values) suggested that roll motion was less influential than lateral motion.

The authors suggested that the correlation values could be used to form a new lateral acceleration frequency weighting for the application of predicting motion sickness in trains. A possible issue with this suggestion is that the correlations indicate the degree of linear association between the lateral accelerations and motion sickness; they do not indicate the gain between motion sickness and the lateral accelerations (i.e. the degree by which motion sickness changes for a given change in lateral acceleration) and thus cannot strictly be used to form an acceleration frequency-weighting.

The conclusions also may be contradictory: at low frequencies, passengers in tilting trains are exposed to less lateral acceleration but more roll motion than conventional trains, hence it would be expected that tilting-trains would cause less sickness. Further analyses of the Japanese data are required to identify the nature of lateral and roll oscillations to which passengers were exposed and to better understand the influence on motion sickness of these co-varying factors.

2.6.4 Summary and conclusions

Studies of motion sickness in conventional trains, or in tilting-trains with their tilt mechanisms inoperative, repeatedly report only a small incidence of motion sickness. Anecdotal evidence and studies of motion sickness in tilting-trains repeatedly report that tilting-trains can have a larger nauseogenic potential.

Motion sickness tends to increase with increasing roll-compensation of lateral acceleration. The causes of motion sickness in tilting-trains have been variously attributed to the 'swing' (lateral accelerations due to roll in passively tilting-trains) at frequencies less than 1 Hz, the frequency weighted roll acceleration dose, and lateral accelerations in the frequency range 0.25 to 0.32 Hz.

The reviewed studies have sought to define a unique predictor of motion sickness from any one of the vertical, the lateral or the roll accelerations. That these studies have reported contrary findings regarding the relative importance of these variables is not surprising given their covariant characteristics. A more complete analysis of motion sickness in tilting-trains must consider more fully the relationships between the lateral, vertical and roll motions when relating them to reports of motion sickness.

2.7 STUDIES OF MOTION SICKNESS IN NON-RAIL TRANSPORT

2.7.1 Introduction

A specific aim of the thesis was to investigate the causes of motion sickness in tilting-trains. Experimental studies of motion sickness in fixed guide-way systems was treated in the previous section; however, studies of motion sickness in non-rail modes of transport also discuss material relevant to the influence of motion on motion sickness. Studies of motion sickness on sea, air and land transport will be discussed sequentially. Findings from general surveys of motion sickness history isolated from motion exposure will not be covered.

2.7.2 Sea transport

Sea travel has been a long recognised cause of motion sickness, as is evident from the word nausea, meaning 'an inclination to vomit', which derives from the Greek word for ship, "naus".

Motion characteristics

Data concerning the general characteristics of ship motions have been surveyed (Griffin, 1990): Ship motions vary according to the sea conditions, and the principal effect of deteriorating conditions is an increase in the magnitude of the motions rather than a change in their frequency.

Ship rotations cause translation at locations away from the centre of rotation. Therefore, passenger motion exposure depends on the position within the ship; lateral motion increases with height above the centre of rotation and vertical motion increases with horizontal displacement from the centre of rotation. In passenger ships, vertical (heave) and pitch motions are highly correlated, as are lateral (sway) and roll motions. Typically, vertical motion is maximal at the bow or stern of the vessel and minimal amidships.

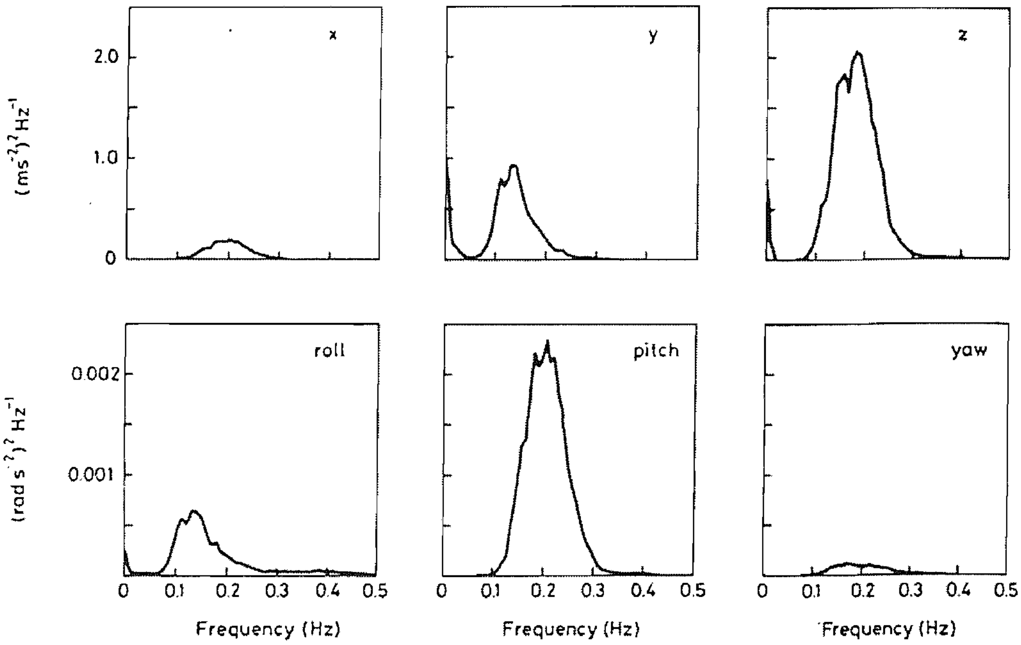

Figure 2.13 Typical acceleration power spectra for translational and rotational ship motion for 4-hour journey. Resolution = 0.01 Hz (Lawther and Griffin, 1986).

Furthermore, the motions in all axes are covariant such that when vertical motion is maximal, motion in all other axes also tend to be maximal.

Figure 2.13 shows acceleration power spectra obtained during a study of a motion sickness on a car passenger ferry (4000 tonnes) (Lawther and Griffin, 1986). The peak fore-and-aft (*x*-axis; surge) and pitch oscillation frequencies of the ship tended to remain within the region of 0.2 Hz (either within or between voyages). Peak lateral (*y*-axis) and roll oscillation frequencies varied slightly between 0.1 and 0.2 Hz, possibly depending on the ship's course relative to the waves. Irrespective of sea state the magnitude of the vertical (*z*-axis) motion was greater than in the two other translational axes, and the fore-and-aft (*x*-axis) was the least. Yaw magnitudes were usually lower than pitch or roll magnitudes. Larger ships tend to cause lower frequencies of peak oscillation magnitude, but the variation is not great and the principal vertical acceleration remains close to 0.2 Hz (Griffin, 1990).

Sickness

Lawther and Griffin investigated motion and reports of motion sickness aboard civilian passenger ships during 114 voyages on 9 different vessels (Lawther and Griffin; 1986, 1987, 1988a, 1988b). With 3-hour voyages on various ships, an approximately linear relationship, shown in Figure 2.14, was obtained between the root-mean-square vertical acceleration magnitude and both the vomiting incidence and the mean illness ratings. Compared with motions in other axes, motion sickness was most correlated with vertical motion and pitch motion, although as discussed above the motions are covariant and highly correlated.

The incidences of sickness in males and females were significantly different, in the approximate ratio of 3:5 (Lawther and Griffin, 1987).

A series of studies of personnel on Navy vessels (Bles *et al.*, 1988 and 1991) suggested that roll motion combined with vertical motion contributes to motion sickness on ships and that the illness may be dependent on the roll angle. In the former study the authors did not perform statistical or frequency analyses and during the studies the movements of the personnel were uncontrolled. No statistical analyses were presented in the latter study.

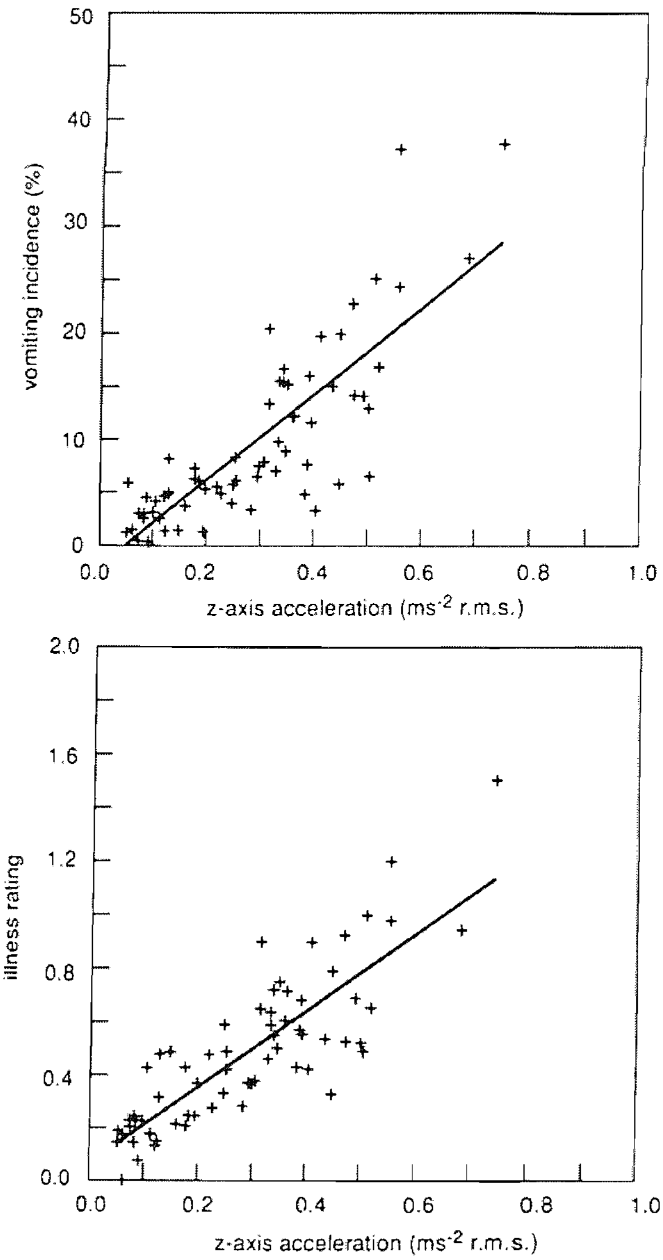

Figure 2.14 Effect of magnitude of vertical ship motion on vomiting incidence and mean illness rating during 3 h of exposure on ships (Griffin, 1990).

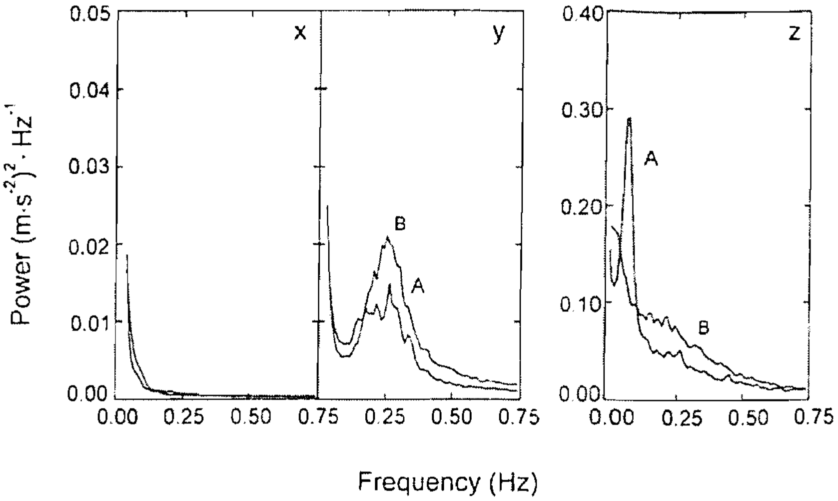

Figure 2.15 Translational acceleration power spectral density functions averaged across 37 flights on two aircraft types. A = 7026 kg payload plane (N = 10), B = 3184 kg payload plane. Resolution = 0.01 Hz (Turner *et al.*, 2000).

2.7.3 Air transport

It was suggested that the incidence of motion sickness in large passenger aircraft declines as the cruising altitude increases and the regions of turbulent air decrease (Griffin, 1990). For smaller aircraft incapable of reaching high altitudes the problem remained.

Motion characteristics

Thermal and ground turbulence at low altitudes, clear-air turbulence at high altitudes, and automated or manual control of the aircraft were thought to cause aircraft motions at frequencies below 0.5 Hz (Turner *et al.*, 2000). The influence of turbulence and control were thought to be moderated by the size, speed and design of the aircraft (e.g. wing loading, aerodynamics) and the weather conditions (Griffin, 1990).

There has been a scarcity of systematic studies of aircraft motion and air-sickness, however Turner *et al.* (Turner *et al.*, 2000) studied 37 journeys with two types of plane (capable of maximum payloads and cruising altitudes of 3184 kg and 7026 kg and 2100 m and 6000 m respectively). As shown in Figure 2.15 the studies revealed similar acceleration power spectral densities in each translational axis for both types of plane, despite differences in the aircraft dynamics and the variety of routes and weather conditions encountered. Greater root-mean-square magnitudes of motion were encountered on smaller aircraft; however the differences were not significant. Of the translational motions recorded, the acceleration magnitudes in the fore-and-aft axis were the lowest, with most energy at frequencies below 0.1 Hz (increasing rapidly with decreasing frequency); little fore-and-aft acceleration was experienced during cruising and the motions were thought to mostly arise from changes in speed and attitude during take-off and on approach to landing. A similar increase of acceleration with decreasing frequency below 0.1 Hz was observed for lateral acceleration, however a further peak in the spectra was observed at 0.25 Hz for both aircraft. The acceleration components less than 0.1 Hz were again attributed to manoeuvres incurred during take-off and the approach to landing, whilst the peak at 0.25 Hz was accredited to the aircraft's response to lateral air displacements (gusting), and possibly to aircraft stability during take-off and approach to landing. Below 0.5 Hz vertical motions also tended to increase with decreasing frequency and increased vertical acceleration was apparent following take-off and approach to landing and with periods of air turbulence. Rotational motions were not recorded explicitly during the flights, however they have an inherent influence in the measured linear acceleration; linear accelerometers are sensitive to translational accelerations and changes in aircraft attitude (orientation with respect to gravity).

Sickness

Turner *et al.* reported (Turner *et al.*, 2000) no significant differences in illness with two types of aircraft in their study of air-sickness. Over all flights, less than 1% of passengers vomited and the incidence of illness was 16.2%, which was lower than that reported during similar trials at sea and in land transport. The authors suggested that sickness was associated with low-frequency lateral and vertical motion below 0.5 Hz, resulting from air turbulence and from variations in aircraft stability following take-off and on approach to landing. A single motion could not be identified as the principal cause of sickness, since the lateral and vertical motions occurred simultaneously, although aircraft manoeuvres or turbulence that produced simultaneous lateral and vertical motions were suggested as most likely to have induced sickness.

2.7.4 Land transport

Excluding studies of fixed guide-way systems, only four studies of motion sickness in land transport have recorded motion sickness whilst simultaneously measuring vehicle acceleration. The two earliest studies investigated respectively the effect of posture and the effect of vision in cars undergoing rectilinear fore-and-aft accelerations. A study of motion sickness in public road transport investigated the effects of driver, route and vehicle, whilst a later study investigated the effect of visual field on motion sickness in cars with 'normal' urban driving conditions. The reported aims and conditions of the studies of motion sickness in road transport differ significantly from one another, such that each study is reviewed separately.

'Dependence of motion sickness in automobiles on the direction of linear acceleration'

Vogel *et al.* hypothesised that otolith stimulation by linear acceleration in an ambulance car is sufficient to elicit motion sickness (Vogel *et al.*, 1982). In their study, a total of 38 volunteers received linear acceleration in one of three positions with their heads restrained: (1) sitting upright facing forward in the car, (2) lying supine on a stretcher head forward, and (3) lying supine head rearward.

Typical car-referenced accelerations are shown in Figure 2.16. The vertical (g_z) and lateral (g_y) accelerations were assumed to be negligible, whereas the fore-and-aft (g_x) accelerations shows periods of weak acceleration (0.15 g) followed by periods of relatively sharp deceleration (-0.75 to –0.95 g), as elicited by braking. The average duration of each test was 10.3 minutes, during which an average of 29 braking-manoeuvres were completed (equivalent to one braking test every 21 seconds or approximately 0.05 accelerating-braking cycles per second).

The incidence of motion sickness in the sitting position (approximately 60%) was almost twice as high as when lying on a stretcher in the supine position (approximately 30%), regardless of whether the head or feet faced forwards when supine. The authors proposed that in the absence of rotational stimulation the motions were mediated by the otoliths rather than the semicircular canals. Nevertheless, due to the constant Earth-vertical gravitational force, the resultant gravito-inertial force would rotate. The authors concluded that accelerations in head x-axis are more nauseogenic than those in the head z-axis.

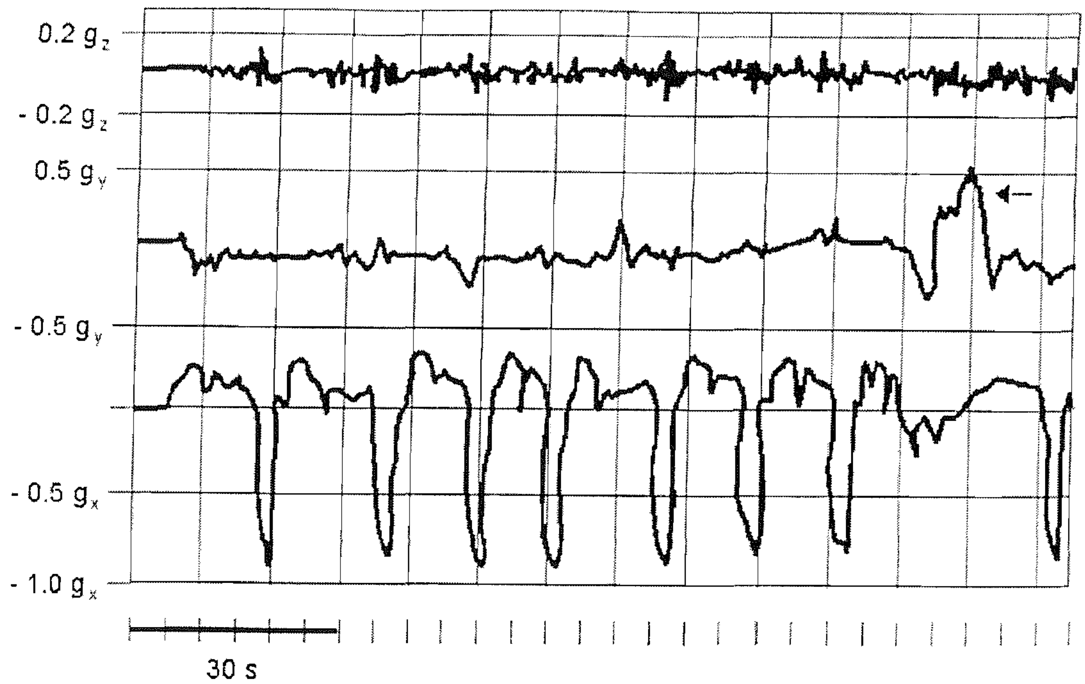

Figure 2.16 Acceleration time histories for vertical (g_z), lateral (g_y) and fore-and-aft (g_z) motion reproduced (Turner, 1999) from Vogel *et al.* (Vogel *et al.*, 1982).

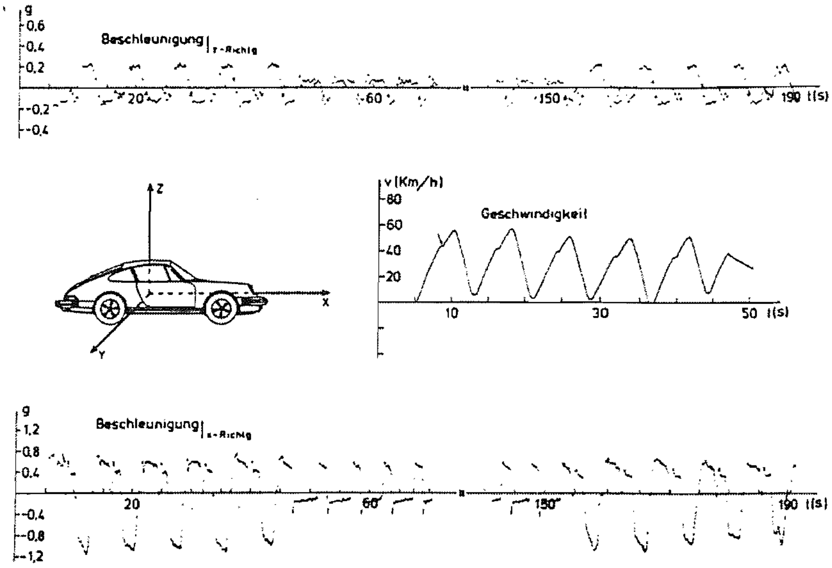

Figure 2.17 Vertical acceleration (top plot), fore-and-aft velocity (middle plot), and fore-and-aft acceleration (bottom plot) measured during heavy acceleration and braking manoeuvres in a road car (Probst *et al.*, 1982).

'Visual prevention of motion sickness in cars'

The influence of visual-vestibular interactions on motion sickness in cars on the road was tested by Probst *et al.* (Probst *et al.*, 1982). Subjects were exposed to predominantly linear accelerations, produced by repetitive acceleration and deceleration (braking) of the car. Three different visual conditions were presented without head restraint in a randomised order over three consecutive days: (1) eyes open with view of direction of travel; (2) eyes closed; and (3) eyes open, with head enclosed by a foam box lined with a map.

Each exposure consisted of a battery of acceleration and braking manoeuvres, performed over a road of length 1.7 km, repeated four times. Each battery lasted approximately three minutes. Prior to each repetition the car returned over the 1.7 km road length to the initial starting position (a "passive" motion phase). Accelerations recorded during the manoeuvres are shown in Figure 2.17. The peak accelerations within each battery of manoeuvres can be described as follows: 5 repetitions of 0.5 *g* acceleration, up to a velocity of approximately 55 km/h, and -1 *g* heavy braking to standstill; 20 repetitions of 0.5 *g* acceleration from 25 km/h to 40 km/h followed by -0.1 *g* engine braking; 5 repetitions of 0.5 *g* acceleration, up to a velocity of approximately 55 km/h, followed by -1 *g* heavy braking to standstill.

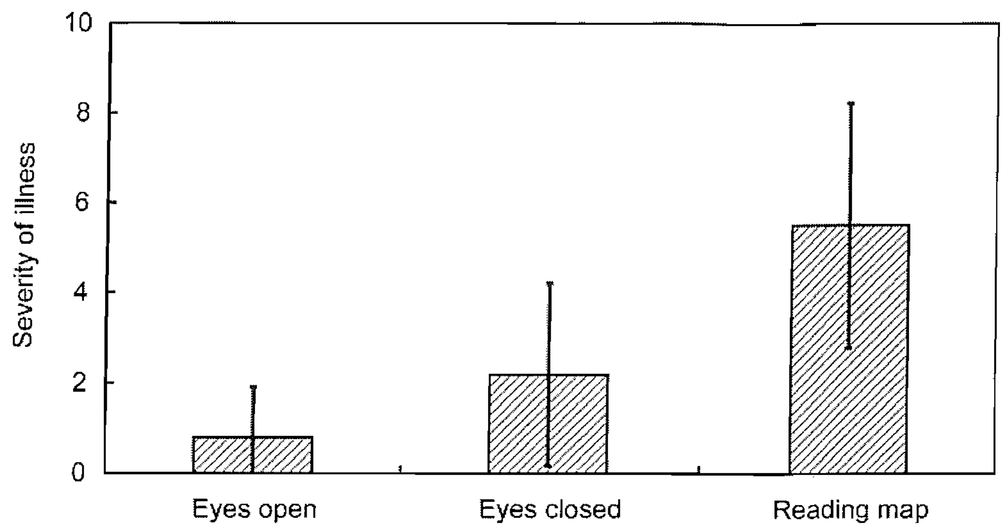

Figure 2.18 Mean illness severity, rated on a 10 point scale, in each visual condition with linear fore-and-aft acceleration in a car (calculated using data from Probst *et al.*, 1982). Error bars = standard deviation.

The subsequent severity illness was rated on a 10-point scale. Figure 2.18 shows for each visual scene condition the mean and standard deviation reported illness severity. Reading a map with no external view provoked most sickness and having a normal 'eyes open' view provoked the least sickness. The authors concluded that the provision of "ample peripheral vision of the relatively moving surround is the best strategy to alleviate car sickness".

'Motion sickness in public road transport'

The effects of coach motion, vision and passenger susceptibility on motion sickness were investigated in a questionnaire survey of 3256 passengers in 56 private hire coach journeys (Turner and Griffin; 1999a, 1999b, 1999c). Five types of coach were used throughout the study (type A = 74 seats, 24 journeys; type B = 76 seats, 21 journeys; type C = 69 seats, 6 journeys; type D = 76 seats, 3 journeys; type E = 53 seats, 2 journeys) and acceleration power spectral density functions were calculated for all journeys. Over all journeys, 28.4% of passengers reported feeling ill, 12.8% reported nausea and 1.7% reported vomiting.

The averaged acceleration power spectral density functions for each axis in each type of coach are compared in Figure 2.19 (Turner and Griffin, 1999b). Fore-and-aft, lateral and yaw acceleration power spectra decreased rapidly with increasing frequency, with the greatest energy in these axes at frequencies less than 0.5 Hz. Vertical, roll and pitch acceleration spectra showed differences, but only above 0.5 Hz. The mean frequency weighted root-mean-square accelerations in each axis were compared across coaches; accelerations in the vertical and roll axes were significantly different, however accelerations in the fore-and-aft, lateral, pitch and yaw axes were not.

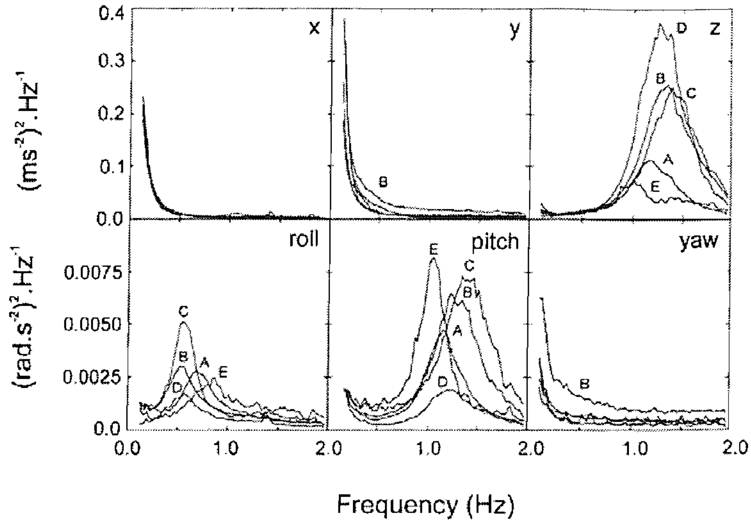

Figure 2.19 Mean acceleration power spectral density functions for five types of coaches (A – E). Resolution = 0.02 Hz (Turner and Griffin, 1999b).

With 24 journeys of duration 0.9 h to 4.8 h undertaken in a type A coach, the dominant frequencies of acceleration in each axis varied only slightly. With journeys classified as "predominantly motorway" (n = 34) or "predominantly cross-country" (n = 22) significantly greater W_f frequency-weighted (see Section 2.10.3) root-mean-square lateral, roll and yaw accelerations were found in the cross-country routes compared to the motorway routes (Turner and Griffin, 1999b). There were no significant differences between the root-mean-square acceleration magnitudes in the fore-and-aft, vertical and pitch axes on the two different route types.

The mean frequency-weighted root-mean-square acceleration in each axis produced by five drivers completing five or more coach journeys were compared (Turner and Griffin, 1999b). There were no significant differences with respect to the main route types or lengths (in km) of the journeys that the drivers used, however significant differences in acceleration magnitudes were found between drivers for fore-and-aft, lateral, vertical, roll and yaw axes.

When comparing the effect on translational acceleration of location within the coach, the greatest differences were found to occur along the length of each vehicle (Turner and Griffin, 1999b). Figure 2.20 shows the translational accelerations measured 0, 6 and 12 m from the front of a type A coach during a 2.3 hour journey. Below 0.25 Hz the variation in power is greatest in the lateral axis, with the magnitude increasing with increasing distance from the front of the coach.[5] Magnitudes of vertical acceleration were greater at the front and rear of the coach than in the centre.

Predictions from the motion sickness dose value model (see Section 2.10.3) underestimated the reports of sickness. When compared to nauseogenic vertical motions, the authors suggested that humans are more sensitive to nauseogenic horizontal motions, thus the frequency-weightings, and frequency ranges, might be different for the two axes. The authors suggested that more systematic investigation of the effect of frequencies of lateral oscillation less than 0.125 Hz is needed.

Turner and Griffin investigated the effect of forward view on motion sickness (Turner and Griffin, 1999c). Irrespective of motion magnitude, poorer forward vision was positively correlated with sickness, such that illness occurrence amongst passengers was approximately three times higher for passengers with no view of the road ahead than for passengers with good forward visibility; however, vehicle motion was found to be more influential than visual information in determining sickness.

Passenger age, travel history (travel frequency and sickness history) and gender were the most highly correlated measures of passenger susceptibility to motion sickness on coaches (Turner and Griffin, 1999a). Out of those passengers reporting illness, a ratio of four females to three males was found (Turner and Griffin, 1999a).

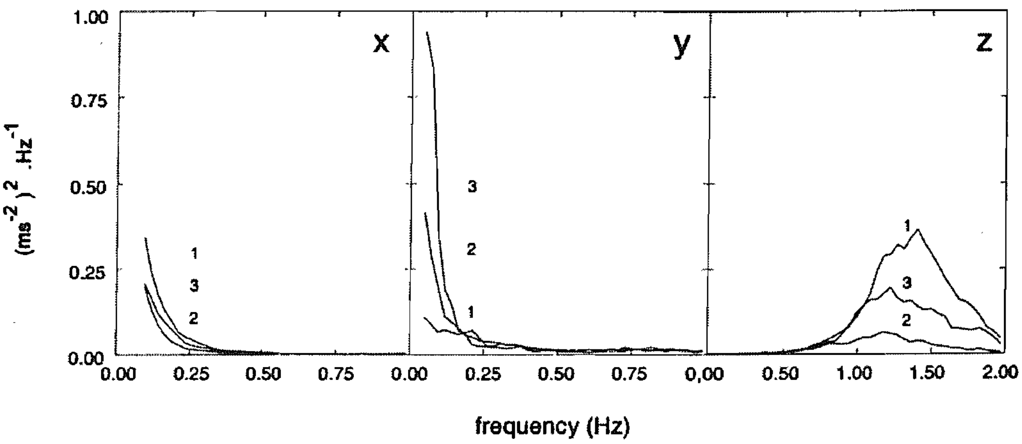

Figure 2.20 Positional variations in translational acceleration with vehicle length for a 2.3-hour journey on a type A coach. Numbers indicate distance of the measurement position from the front of the coach: 1 = 0 m; 2 = 6 m; 3 = 12 m. Resolution = 0.02 Hz (Turner and Griffin, 1999b).

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[5] When negotiating a curve the front wheels trace a larger arc than the rear wheels: the rear wheels follow a smaller apparent curve radius thus increasing the lateral acceleration. The effect is worse for longer coaches and tight corners (Turner and Griffin, 1999b).

'Experimental studies of the effects of the visual field on motion sickness in cars'

Griffin and Newman conducted a series of experiments including a total of 15 visual conditions to investigate the effects of visual field on motion sickness in a car and a minivan (Griffin and Newman, 2004). The experiments were performed over a fixed suburban route with a maximum speed of 30 miles per hour (48 kilometres per hour). Groups of 20 subjects were individually exposed to one journey in only one condition. Linear accelerations were measured on the floor of each vehicle and motion sickness dose values (see Section 2.10.3) were calculated in each axis for each journey to ensure that motion conditions were matched across conditions.

In their first experiment Griffin and Newman compared the effect on motion sickness of various combinations of forward and side view within a car: (1) unrestricted forward and side view, (2) no view (blindfolded), (3) no forward view or side view, (4) forward view, without side view, and (5) side view without forward view. Less illness was reported by those subjects provided with a forward view, suggesting that a forward view is beneficial to passengers. Blindfolded subjects reported similar sickness to those subjects exposed without a forward view (with or without side view), thus it was concluded that closing the eyes would not reduce sickness in cars.

With two different vehicles and drivers in a second experiment, Griffin and Newman explored the effect on motion sickness of changes in the use of headrests and changes in the visual scene arising from changes in passenger seat location: neither was found to have had a significant effect on the development of motion sickness.

When comparing motion sickness with similar forward views as studied in both experiment 1 and experiment 2, more illness was reported in the second experiment than within the first experiment. The authors suggested that the difference could not be explained by changes in the visual field alone: although similar motion sickness dose values were obtained in both conditions, examination of the acceleration spectra revealed appreciably more low frequency motion in the fore-and-aft and lateral directions in the second experiment (Figure 2.21). Any possible influences of these low frequency motions would have been excluded from the motion sickness dose values due to the band-pass nature of the W_f frequency weighting. From this finding the authors suggested that motion sickness in cars might be influenced by fore-and-aft and lateral motions at frequencies below 0.08 Hz.

With no direct external view, a real-time video view of the road ahead was provided to the rear seat car passengers. With this view, the authors reported that the video display did not alleviate sickness, possibly because the display failed to present the information needed to give the cues present during a direct forward view, or because while presenting this view it also presented visual stimuli that cause motion sickness.

In the final experiment of the series the authors found that motion sickness was not affected by adding or removing the provision of the foreground view with an otherwise normal external view. In this experiment both male and female subjects were exposed. Women tended to report more illness than men but the difference was not significant, possibly because of the large variability and small number of subjects.

In their conclusion the authors stated that the visual field observed by passengers has a large influence in moderating motion sickness and the direct visual perception of some stationary objects in the distance seemed beneficial.

2.7.5 Discussion and conclusions

The dominant motions in large passenger ships are vertical accelerations arising from vertical translation and roll and pitch rotation as a ship negotiates its passage through waves. Motion sickness was found to be approximately linearly dependent on the magnitude of the vertical acceleration, although the precise influence of the combined translational and rotational components was not known.

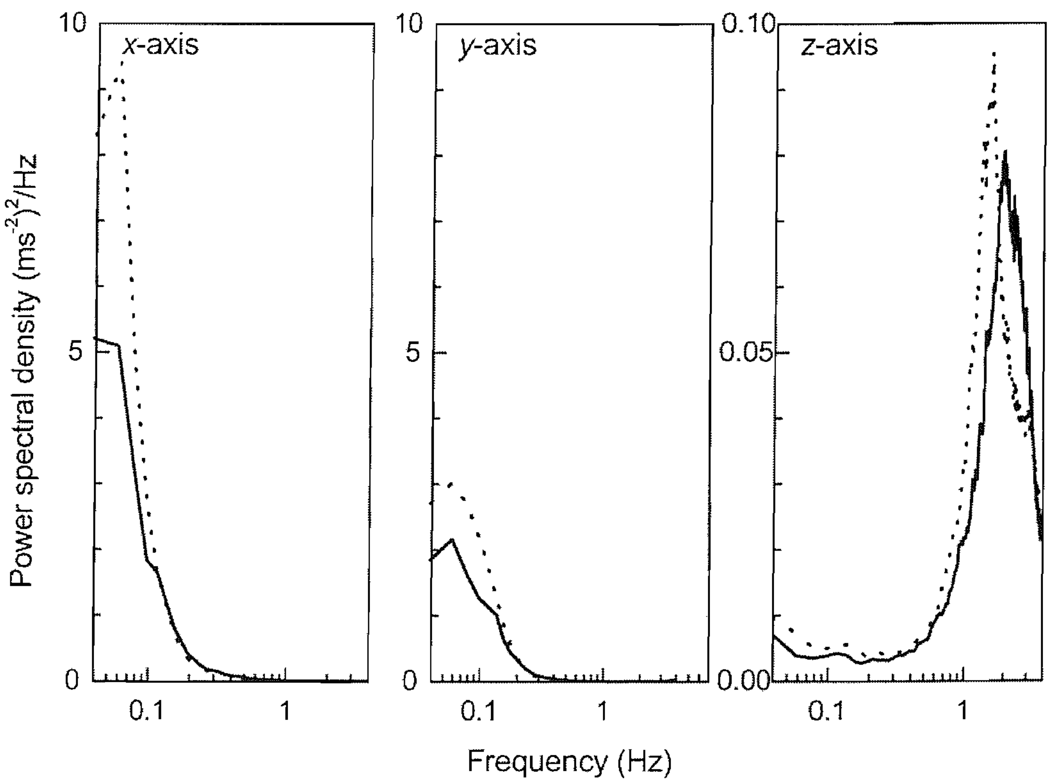

Figure 2.21 Median power spectral densities measured within a condition (unrestricted forward and side view) repeated in experiment 1 (solid line) and experiment 2 (dotted line) (Turner *et al.*, 2000).

The causes of motion sickness on aeroplanes were thought to be combinations of lateral and vertical acceleration arising from aircraft manoeuvres and turbulence.

A study of the effect of posture (upright or supine) with fore-and-aft accelerations in cars suggested that stimulation through the head *x*-axis was more nauseogenic than stimulation through the head *z*-axis.

With fore-and-aft oscillation in a car, motion sickness was least with the eyes open, slightly worse with the eyes closed and much worse whilst reading a map with no external view.

During a study of motion sickness on coaches, motion sickness was found to increase with increased exposure to low frequency (below 0.5 Hz) lateral and, to a lesser extent, fore-and-aft coach accelerations. Compared to the “predominantly motorway” routes, nausea occurrence was greater on the “predominantly cross-county” routes where magnitudes of lateral acceleration were significantly higher. Reports of motion sickness were greater with drivers who averaged higher magnitudes of lateral and fore-and-aft motion. The location of passengers within the coach influenced their exposure to lateral acceleration and their subsequent motion sickness such that both tended to increase from the front to the rear of each vehicle.

Changes in the visual scene had a significant influence on motion sickness in cars and lateral oscillations at frequencies below 0.08 Hz may also contribute to motion sickness in cars.

2.8 THEORIES OF MOTION SICKNESS

2.8.1 Introduction

Contemporary models, created to explain environments which cause motion sickness, have been developed on the basis of sensory conflict. This section summarises this concept, its evolution and evaluates recent models.

2.8.2 Sensory conflict

The sensory conflict principle first was expressed by Claremont (1931):

> "Ask the cause of sea-sickness, and you will be told vaguely that it is due to the motion. ... It is a discrepancy between the information given us by one set of sensations, and that given us by another set. This must be the causative fact."

Irwin specifically recognised the role of the vestibular system as an aetiological factor in motion sickness (Irwin, 1881):

> "...our bodies are endowed with ... a supplementary special sense ... the function of which is to determine the position of the head in space ... This faculty of equilibrium ... is in the semicircular canals of the internal ear, which may for practical purposes be regarded as the organs of equilibration".

A subsequent observation of some consequence was that individuals who lack inner ear vestibular function are immune to motion sickness (James, 1882).

Situations provoking sensory conflicts have been organised into two categories; inter-modal and intra-modal (Reason and Brand, 1975). However, the concept of a simple sensory conflict appeared insufficient to describe the habituation response to motion sickness. Griffin (Griffin, 1990) notes that much sensory information has little absolute significance: we learn the meaning of most stimuli and adjust to changes in sensory experiences produced by stimuli.

2.8.3 Gravito-inertial force resolution

From inertial navigation techniques, Mayne (Mayne, 1974) proposed a frequency segregation mechanism for human gravito-inertial force resolution of vestibular sensory information: otolith afferent information was resolved by attributing the low frequency components to gravity and the high frequency components to linear acceleration. Such a mechanism might be realised by a low pass filter of the afferent vestibular information. Mayne went on to suggest that motion sickness arises from situations in which gravity is interpreted as acceleration.

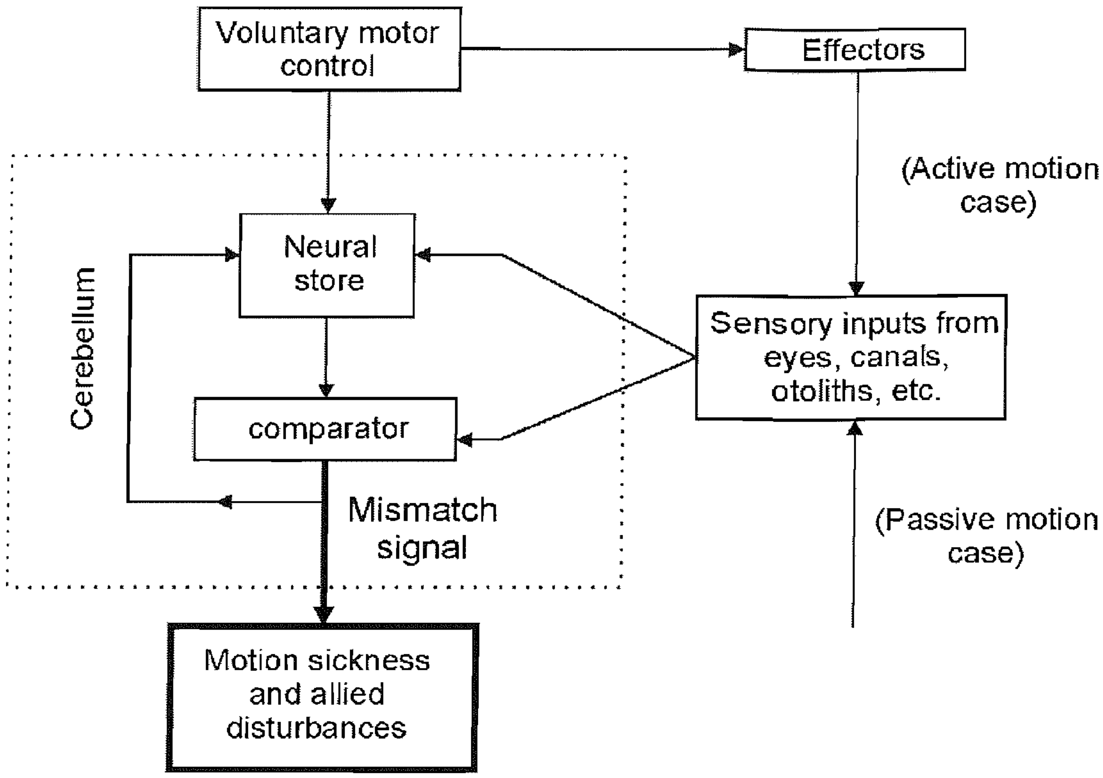

Figure 2.22 The neural mismatch model (adapted from Reason, 1978).

2.8.4 Sensory rearrangement theory and neural mismatch

The "sensory rearrangement theory" or the "neural mismatch theory" of motion sickness was developed to rationalise the effect of habituation on motion sickness (Reason and Brand, 1975):

> "All situations which provoke motion sickness are characterised by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular system and the non-vestibular proprioceptors are at variance not only with one another, but also with what is expected on the basis of past experience".

The notion of sensory rearrangement (Held, 1961) proposed that the total pattern of sensory input is compared to the pattern expected on the basis of past experience, or what Held termed "exposure-history". The principle had its origin in the re-afference principle (von Holst, 1954).

Reason hypothesised that within the central nervous system there is a comparator and neural store where signals from the sensory receptors are correlated (Figure 2.22): when an active movement is initiated, a copy of the motor command signal (efference copy) is transmitted to the neural store where it retrieves sensory afferent traces previously associated with that command (i.e. the expected sensory information; sometimes defined as "re-afference"). A 'comparator' compares the expected signal traces to the incoming afferent sensory information. Discrepancies between the incoming sensory afference and the stored patterns create a mismatch signal which triggers various neural mechanisms mediating the nausea syndrome and allied perceptual disturbances. The nausea response is assumed to be proportional to the degree of mismatch. Reason hypothesised that some correlate of the mismatch signal feeds back to modify the neural store (adaptive feedback) so as to provide a mechanism for habituation.

2.8.5 Stott's postulates

Stott (Stott, 1986) re-interpreted the sensory conflict hypothesis of motion sickness using three postulates governing the physical relationships between information from the various sensory modalities (in an Earth-bound pedestrian environment).

Postulate 1: Visual-vestibular interaction

> "Angular motion of the head in one direction must result in angular motion of the external visual scene to the same extent in the opposite direction. A similar relationship exists for linear motion."

Stott commented, "The contrary motion of the visual scene is not perceived as such. Provided this rule is obeyed, the brain perceives the external world as being fixed in space. Only if the rule is violated, for example, by wearing magnifying spectacles, does the world appear to be in motion during head movements. For translational motion the amount of relative motion of an object in the visual scene depends on the distance of the object: close objects undergo large relative motion while objects at optical infinity undergo none at all."

Postulate 2: Canal-otolith interaction

> "Rotation of the head, other than in the horizontal plane must be accompanied by an appropriate angular change in the direction of the linear acceleration due to gravity."

The rule implies a fixed relationship between semi-circular canal afference, indicating head angular velocity, and otolithic afference, signalling forces due to gravity.

Postulate 3: Utricle-saccule interaction

> "Any sustained linear acceleration is due to gravity, has an intensity of 1 g (9.81 ms^{-2}) and defines 'downwards'".

The utricle and the saccule sense linear accelerations in the transverse and sagittal planes respectively. The utricle and saccule components combine to yield sensory information about the magnitude and direction of linear acceleration (i.e. the gravito-inertial force).

Normal locomotor activities produce only transient accelerations which, over time periods of the order of 1-second, average to zero in the horizontal plane and average to 1 *g*, the intensity of gravity, in the vertical direction. Any sustained acceleration is therefore perceived as being due to gravity and there is expectancy that it will remain constant in magnitude and direction. In consequence, a fixed relationship exists between utricular and saccular inputs. A sustained change in linear acceleration sensed through one component must be accompanied by an appropriate change in magnitude or direction sensed by the other component indicative of a change in head angular position within a 1-*g* environment.

2.8.6 A heuristic mathematical model

Oman (Oman, 1982) developed a "sensory-motor conflict theory" of motion sickness described as a "heuristic [learning] mathematical model for the dynamics of sensory conflict and motion sickness" to reconcile the neural mismatch model with a control engineering approach. The conceptual model, based on observer theory, aimed to provide an alternative motivation for the existence and processing of sensory conflict signals, other than they exist to make us sick (Oman, 1990): Oman's observer model, shown in Figure 2.23, assumed that conflict signals are essential for maintenance of balance and control of body movements.

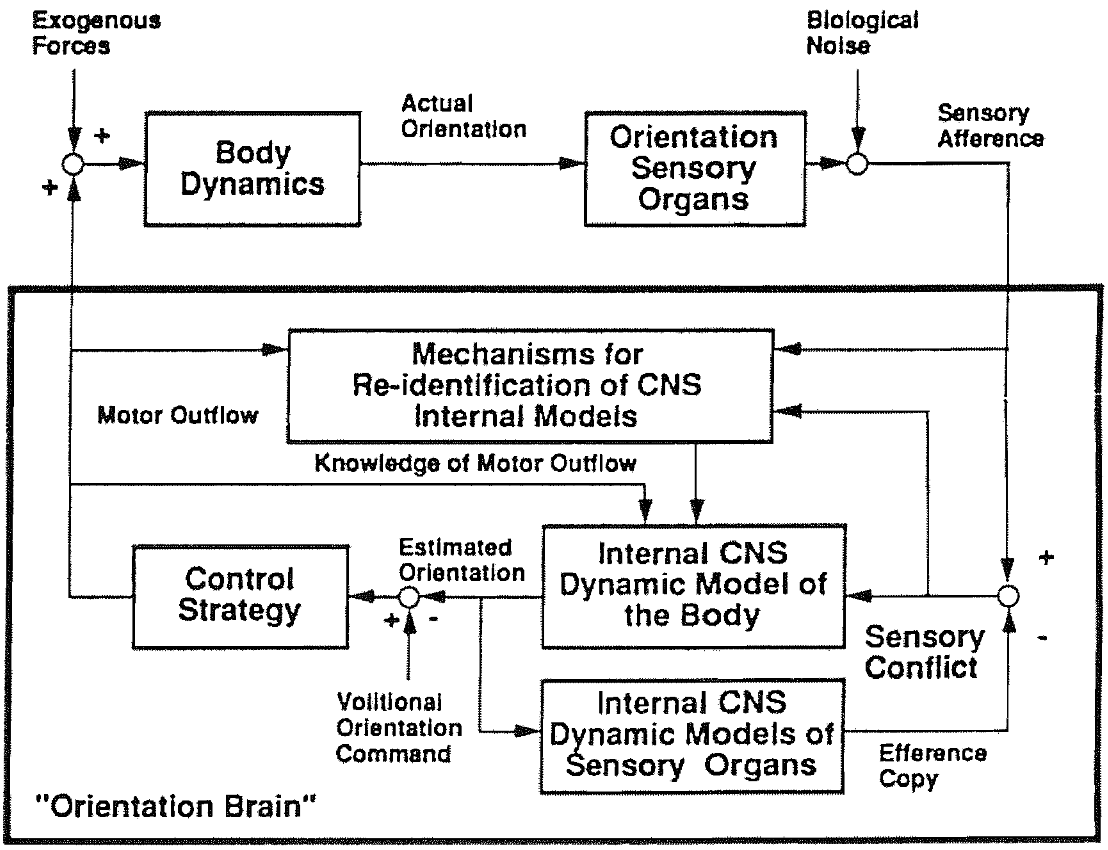

Figure 2.23 A mathematical model for sensory conflict and movement control based on observer theory (Oman, 1982).

It was hypothesised that active control of body movement using a limited set of noisy signals (from the human proprioceptive systems) would require a conflict, or error, processing strategy to trigger corrective postural movements and to update an "internal model" of the behavioural characteristics of the body (i.e. the "adapting feedback", or habituation, as hypothesised by Reason). Mathematically, Oman related motion sickness to the conflict or error as determined from a vector difference between a vector representing all the available afferent sensory information and a vector representing the expected sensory information, such that as the difference grows, the chance of motion sickness and the severity of motion sickness increase.

The "observer" portion of the model assumed that internal CNS models of the body and sensory organ dynamics are used to continuously estimate the 'dynamic body state' in order to close the control loop: estimates of the expected sensory signals are created from estimates of body motion and internal CNS models of the dynamics of the various proprioceptive systems. The expected sensory signals are then subtracted from the measured sensory signals to form the conflict signal. The observer model uses the sensory conflict, or error, signal to drive the estimated orientation vector towards reality, thus the model compensates for conflicts caused by disturbances, or exogenous forces (e.g. stumbling over an obstacle).

A constant high level of conflict was assumed to be indicative that the relationships between the input and output of the body dynamics or sensory systems have changed (i.e. conditions of sensory rearrangement, such as in space). Oman suggested mechanisms within the model whereby the internal models can be adjusted (i.e. model re-identification or sensory-motor learning).

2.8.7 Otolith-tilt reinterpretation hypothesis

An otolith-tilt reinterpretation hypothesis of motion sickness was thought to explain space sickness: Observations of the perception of self-motion during sinusoidal roll (Parker *et al.*, 1985) made between 70 and 150 minutes after landing found that roll was perceived primarily as translation. It was also observed that relative to pre-flight and later post-flight observations the same roll conditions provoked more horizontal eye movements. Later reports confirmed these observations (Reschke and Parker, 1987).

The observations were consistent with the supposition that otoliths in the Earth environment are sensitive to the forces arising from inertial acceleration and the orientation relative to the Earth's gravitational field. In space the force due gravity is negligible and otoliths respond only to translational acceleration. Thus roll and pitch head motions will cause semicircular canals to signal changes in orientation without concurring otolith signals. Thus the potential for sensory conflict exists in the period before habituation to the microgravity environment.

The concept of an "otolith tilt-translation reinterpretation" hypothesis of motion sickness and the findings above are consistent with the intra-vestibular interactions arising from the expected physical relationships as postulated by Stott: the hypothesis explicitly describes a motion sickness mechanism arising from erroneous processing of gravito-inertial force information.

2.8.8 Subjective vertical hypothesis

The subjective vertical hypothesis of motion sickness (Bles *et al.*, 1998) aimed to simplify Reason's sensory conflict hypothesis by assuming that only one type of conflict is sufficient to provoke motion sickness:

> "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 non-vestibular proprioceptors is at variance with the subjective vertical as expected from previous experience."

The hypothesis implies that the causes of motion sickness are disparities between the actual (sensed) orientation with respect to gravity and the estimated (or expected) orientation with respect to gravity. A consequence of the hypothesis is that motion sickness can arise from inappropriate resolution of gravito-inertial forces. By extending Oman's sensory-motor model to include low pass filter elements (Mayne, 1974) to resolve the gravito-inertial forces, Bos and Bles created a quantitative motion sickness model (Figure 2.24). Centrifuge investigations of the subjective vertical utilised static force environments (Bos and Bles, 2002) to determine the filter time constant of approximately 5 seconds.

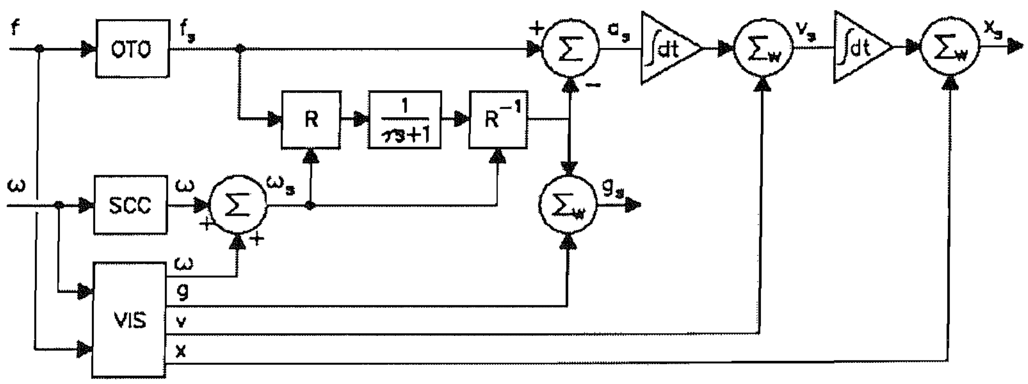

Figure 2.24 Bos and Bles' scheme for resolving the orientation with respect to gravity; *f* represents the specific gravito-inertial force and ω the angular velocity (Bos and Bles, 2002).

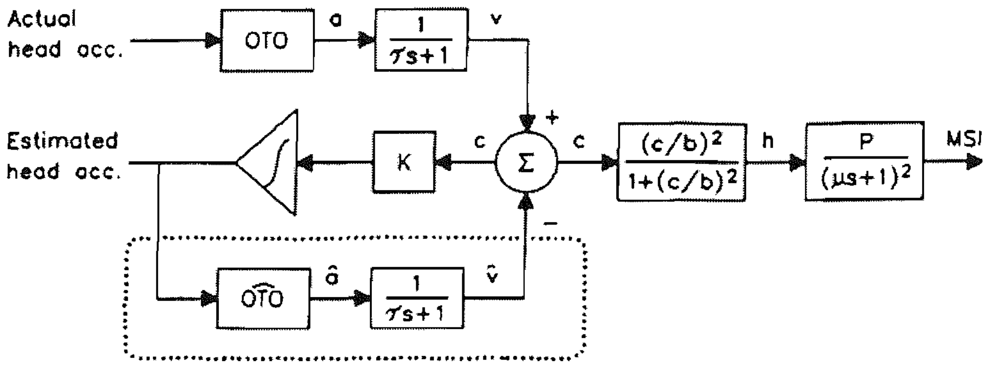

Figure 2.25 Subjective vertical model for passive vertical motion (Bos and Bles, 1998).

Bos and Bles elaborated their model for the case of passive vertical translation without rotation (Bos and Bles, 1998). For this case the model was hypothesised to reduce to the form shown in Figure 2.25. Without angular motion the subject referenced coordinate system remained fixed relative to the Earth-referenced coordinate system. Rotational transformations, required for filtering the otolith signals in a geocentric coordinate system, and afferent information from the semi-circular canals were then hypothesised to be redundant.

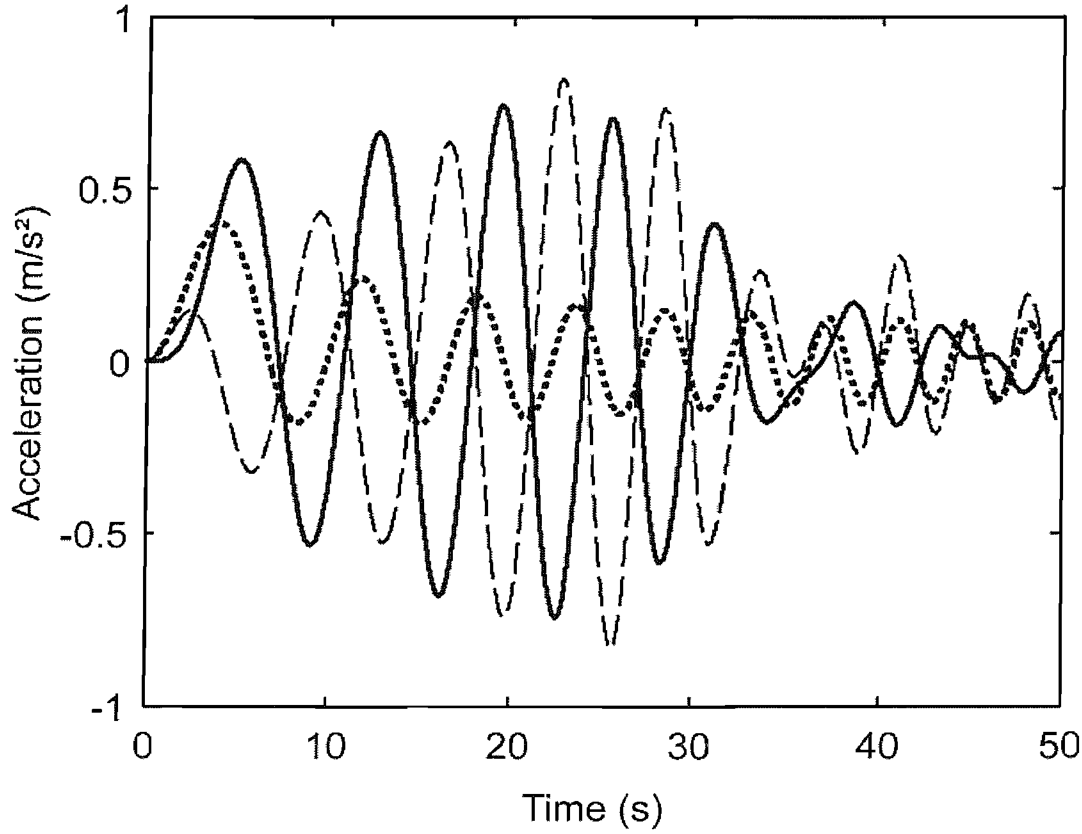

Figure 2.26 Sensed vertical (dotted line), expected vertical (dashed line) and conflict (solid line) signals predicted by the subjective vertical model (Bos and Bles, 1998) for passive vertical motion with a swept sine wave characteristic (Calculated from a MATLAB implementation of the model).

Table 2.6 Subjective vertical model parameters optimised to fit with McCauley motion sickness incidence data.

Model parameters				
$\tau = 5$ s	$K = 5\ s^{-1}$	$b = 0.7\ ms^{-2}$	$\mu = 12$ minutes	$P = 85\%$

The model is summarised as follows: low-pass filtered otolith signals, derived from the gravito-inertial force, form the 'sensed vertical'. A concurrent CNS internal model of the otolith organ and low pass filter network is employed to form an estimate of the orientation with respect to gravity, the 'expected vertical'. The conflict signal, given by the difference between the sensed and expected verticals, is fed back to the internal model to form subsequent estimates of the expected vertical. The development of the motion sickness incidence (MSI) is modelled as a leaky integration of the Hill transformed conflict signal.

The frequency dependence of the model, at constant acceleration magnitude, was demonstrated with a swept sine-wave input. Figure 2.26 shows the predicted sensed vertical, expected vertical and conflict signals with a swept sine-wave input. The conflict signal was at a maximum when the frequency of oscillation was in the region 0.16 Hz and when the difference between the sensed and expected vertical was the greatest. The difference was dependent on the magnitude and phase differences between the sensed and subjective verticals.

Bos and Bles optimised the model parameters (μ, K, b and P) to provide a best fit with the motion sickness incidence data (MSI) obtained by McCauley *et al.* with vertical motion (McCauley *et al.*, 1976; O'Hanlon and McCauley, 1974). The predictions are shown in Figure 2.27 and the optimised model parameters shown in Table 2.6.

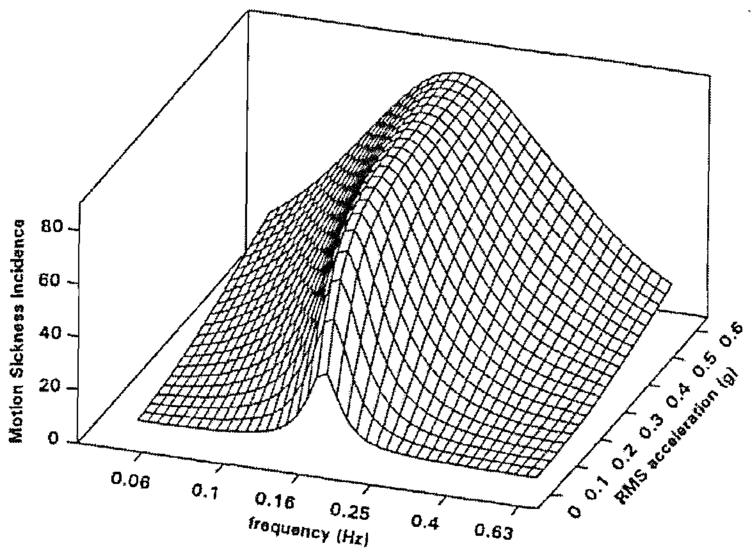

Figure 2.27 Subjective vertical model (Bos and Bles, 1998) prediction of the relationship between the magnitude and frequency of vertical oscillation and motion sickness (% vomiting).

2.8.9 Discussion and conclusions

Mayne (Mayne, 1974) suggested that motion sickness arises in situations where gravity is mistaken for linear acceleration. His hypothesis remained a statement and he did not attempt to test the hypothesis or derive a predictive model of motion sickness from this assumption.

The sensory conflict and sensory re-arrangement theories of motion sickness are qualitative and have little predictive power, such that with these models it is impossible to rank the likelihood of motion sickness in different environments.

In its current state, the sensory-motor conflict hypothesis of motion sickness is not predictive. The model proffered a feedback error function for the hypothesised existence of conflict within the CNS, which arises from comparisons between internal CNS estimates of the body motion state to the sensation of body motion. A related hypothesis, adopted by subsequent models, was that motion sickness was dependent on the magnitude of the vector difference between the sensed and expected states.

Stott's postulates appear to establish violations of the expected state of the physical world arising from perceptions of the space fixed coordinate system, the orientation relative to the force of gravity and the resultant gravito-inertial force. Unlike the sensory rearrangement model, Stott's postulates define an expectation for any given sensed motion. Therefore the postulates allow predictions of motion sickness. Thus far no published studies have used the model to predict sickness and it has yet to be developed into a quantitative model. The suppositions of the postulates are consistent with other contemporary models of motion sickness (e.g. the gravito-inertial force resolution model, the otolith tilt-translation reinterpretation hypothesis and the subjective vertical hypothesis).

The subjective vertical theory implies that motion sickness is caused by a gravito-inertial force resolution mechanism. In contrast to Reason's original statement of sensory rearrangement theory, the subjective vertical theory has the advantage that it might provide a quantitative framework from which to predict motion sickness. There are possible weaknesses within the model, which limit its applicability in its present state: i) the low-pass filter time constants were estimated using only static and not dynamic gravito-inertial force environments; the predictions of motion sickness were wholly dependent on the resultant relative phase and magnitude of the sensed and subjective verticals yet the low-pass filter magnitude and phase responses used to form the sensed and subjective verticals may not be representative of reality. Furthermore, there is some ambiguity as to the exact value of any such time constant, other studies have proposed significantly longer values in the order of 10 – 20 seconds (Bos and Bles, 1998); ii) the data (McCauley *et al.*, 1976; O'Hanlon and McCauley, 1974) to which the model was fitted may be insufficient to justify the assumed form of the model in that there was a paucity of data at frequencies below 0.1 Hz; iii) the role of the semi-circular canals and their integration within the model is not entirely clear and consequently a three-dimensional implementation of the model has not been elaborated in full or published; and iv) it is difficult to make intuitive conceptual predictions of sickness for any given motion.

Mayne's model for gravito-inertial force resolution, Stott's postulates, the otolith tilt-translation reinterpretation hypothesis and the subjective vertical model all predict motion sickness on the basis of sensory conflict/rearrangement arising from processing of the gravito-inertial force: motion sickness is a product of the inherent ambiguity associated with the equivalence of inertial and gravitational forces.

2.9 WHY MOTION SICKNESS?

2.9.1 Introduction

Glaser (Glaser, 1959) compared motion sickness with childbirth:

> "It can cause complete temporary incapacitation without any pathological basis and entirely by reflex mechanisms; though unlike childbirth it serves no obvious purpose at all."

The implication that motion sickness is a chance response to certain provocative stimuli has been challenged by several theories, described in this section.

2.9.2 An evolutionary hypotheses

Claremont (Claremont, 1931) guessed that with incongruous sensory information our "sensory system concludes that we are seriously ill, poisoned probably; hence we vomit – the first precaution of nature's first aid." These sentiments were unrecognised, but further expounded, by Treisman (Treisman, 1977) who suggested that the phenomenon had an evolutionary significance.

Treisman's rationale was that animals must organise their movement in relation to at least three distinguishable sources of spatial information (disregarding auditory information), which are themselves required to be continuously coordinated with one another: proprioceptive inputs, as derived from trunk and limbs; vestibular inputs, which specify the position of the head; and visual inputs, which establish a visual framework. Perceptual adaptation then represents the effects of the mechanisms by which these systems are constantly coordinated with and calibrated against one another. Every movement must involve continuous reference to and coordination between these systems, such that incongruities, failures of correlation between one type of input and another, must constitute an immediate challenge to realign the conflicting systems. Supposing that there are mechanisms for relating visual and vestibular information, and for correlating information about the position of the head and that of the body, failure of the attempt to realign the systems would constitute a challenge to examine the adequacy of each of these control systems and the mechanisms correlating them.

Given this mechanism of the perception of spatial orientation and adaptation, the "apparently disadvantageous response" of motion sickness was attributed to "the occurrence of repeated challenges to re-determine the relations of the eye-head or the head-body systems, or both", rather than motion "per se".

Such challenges would arise with (i) certain types of unfamiliar motion, or (ii) by disturbances in sensory input or motor control produced by ingested toxins. Toxins would be an important cause in nature, the function of the emesis response then becoming obvious. Its occurrence in response to motion would be an accidental by-product of this system.

One apparent failure of the evolutionary hypothesis is its failure to predict the habituation response to motion observed in sufferers of motion sickness. In the context of the evolutionary hypothesis, this response would cause humans to habituate to the ingestion of toxic substances (Webb, 2005), which could have terminal consequences.

2.9.3 Development of the spatial orientation system and motion sickness: a 'hypothetical unifying concept'

According to the sensory rearrangement theory, motion sickness diminishes when central expectation and perceptual-motor reactions are altered by habituation so that the reactions and expectation are appropriate for the situation. Guedry *et al.* (1998) asked:

> "Are motion sickness symptoms during adaptation to new environments a clue to a mechanism that is important in developing synergistic relations among the many components of the spatial orientation system early in life?"

Given that sensory conflict, when vestibular signals are at least one component of the conflict, is innately disturbing and unpleasant, the authors proposed the following:

> "This innate reaction is part of a continuum that operates early in life to prevent development of inefficient perceptual-motor programs. This reaction operates irrespective of and in addition to reward and punishment from goal attainment to yield efficient control of whole body movement in the operating environment of the individual. The same mechanism is involved in adapting the spatial orientation system to strange environments.

It was suggested that the hypothesis explained why motion sickness is associated with adaptation to novel environments.

2.10 LABORATORY STUDIES OF MOTION SICKNESS

2.10.1 Introduction

Laboratory studies have variously investigated the development of the motion sickness syndrome when it is provoked by movement of the body, movement of the visual scene or both. Only studies investigating the effects of movement of the body are reviewed here. Recent studies have tended to explore, sometimes systematically, the effects on motion sickness of the axis, magnitude, frequency and duration of motion and this review aims to identify these.

The review progresses with increasing stimulus complexity, as determined by the number of dimensions in which the gravito-inertial force environment varies and whether rotation occurs, such that it begins with uni-axial oscillations in a vertical axis (with uni-axial gravito-inertial force oscillation), then progresses via horizontal axis oscillations (with 2-dimensional gravito-inertial force oscillation) and develops to studies of combined axes motion, such as lateral and roll oscillation (with 2-dimensional gravito-inertial force motion and simultaneous rotational acceleration).

2.10.2 Studies of motion sickness with vertical translation

Wesleyan University studies of vertical oscillation

A series of motion sickness studies was carried out at the Wesleyan University under the supervision of G. R. Wendt (Alexander *et al.*; 1945a, 1945b, 1945c, 1945d, 1947). An adapted lift device was used to identify the effects of vertical motion on motion sickness. As the acceleration of the device could not be varied continuously, the authors employed a motion waveform alternating between periods of constant acceleration and periods of constant velocity (no acceleration). Subjects were exposed to vertical oscillation for up to 20 minutes within the lift device. A total of 450 naval aviation cadets participated and they were blind-folded and seated without head support. Sickness was rated on a three-point categorical scale between 0 and 2. On this scale, “0” was assigned to those without symptoms and to those who reported dizziness, headache, pallor, sweating which was less than profuse and slight nausea; “1” was assigned to those who reported unequivocal nausea and/or showed profuse sweating; “2” was assigned to those who vomited. The ratings were summed in various ways to give a measure of the nauseogenicity of each condition.

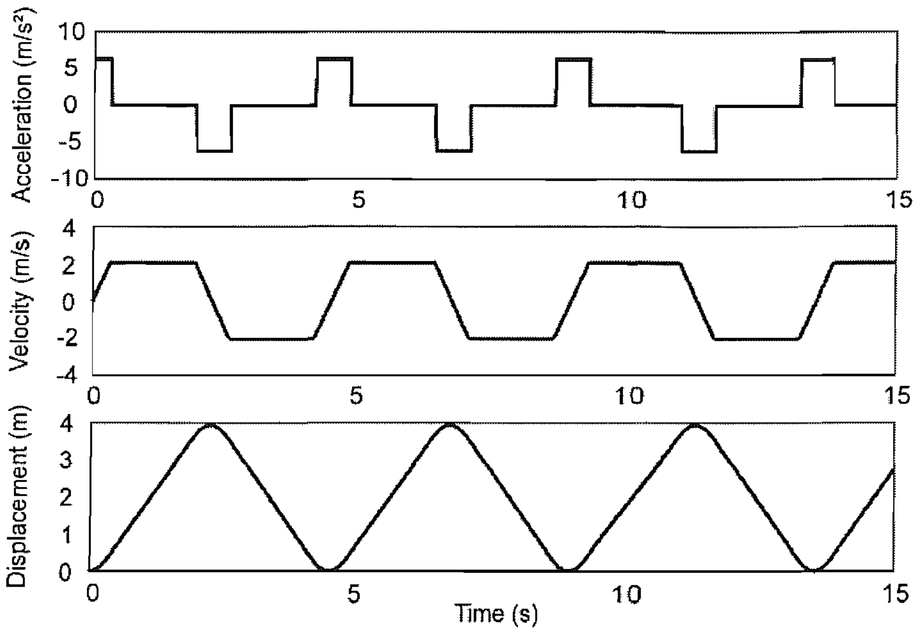

Figure 2.28 Typical idealised waveform from the Wesleyan studies of motion sickness with vertical oscillation (Alexander *et al.* 1945a; 1945b; 1945c; 1945d; 1947). The waveform is estimated for the vertical motion at 0.22 cycles per second.

Whether idealised or recorded, no diagrammatic representation of the waveforms was reported. An idealised waveform, with a cyclic frequency of 0.22 cycles per second, based on the motion characteristics described in the report, is given in Figure 2.28. The acceleration waveform appears as a stepped square or rectangular wave; the velocity waveform appears trapezoidal and the displacement waveform appears approximately sinusoidal.

Within limits, the relative durations and relative magnitudes of the alternating periods of constant acceleration and constant velocity could be varied. Initial experiments were required to identify which of the total cyclic period, the acceleration magnitude and the relative duration of the acceleration and non-acceleration phases was the prime factor influencing motion sickness.

The first study (Alexander *et al.*, 1945a) hypothesised that motion sickness will increase with increasing duration of the period between acceleration and deceleration. Four waves of constant acceleration phase duration, constant peak acceleration and constant peak velocity were examined. As the constant velocity phase period was varied from 0.2 to 1.6 seconds, the wave frequency varied from 0.53 to 0.22 cycles per second. Vertical oscillation at 0.53 cycles per second produced significantly less illness than vertical motions at 0.22, 0.27 and 0.37 cycles per second. Oscillation at 0.27 cycles per second produced most sickness but when compared to oscillation at 0.37 and 0.22 cycles per second, the differences were not statistically significant.

A second similar study (Alexander *et al.*, 1945b) held the wave frequency constant at 0.37 cycles per second but varied the durations of the accelerating and decelerating phases of the vertical motion. The authors examined three waves of constant peak acceleration but varying acceleration phase duration, velocity phase duration and peak velocity. As the constant velocity phase period varied from 0.68 to 1.12 seconds, the peak velocities ranged from 2.0 to 1.0 m/s. Vertical oscillations at 2.0 m/s peak velocity produced most sickness and oscillations at 1.0 m/s produced the least sickness with an approximate ratio of 3:1. The authors concluded that motion sickness depends more on oscillation magnitude than on the temporal separation of accelerations when the wave frequency is held constant.

A third consecutive experiment examined how sickness rates were affected by the peak acceleration magnitude (Alexander *et al.*, 1945c). Four waveforms of varying peak acceleration magnitude but constant peak velocity were studied. With the peak acceleration magnitudes varying in the range from 0.2 to 0.65*g*, the wave frequencies increased from 0.22 to 0.53 cycles per second. Motion sickness was greatest with the low to intermediate acceleration magnitudes that occurred with wave frequencies between 0.22 and 0.37 cycles per second. Least sickness was obtained with oscillation with the highest peak acceleration magnitude, 0.65*g*, and highest wave frequency, 0.53 cycles per second. With the data from the first three experiments, the authors were unable to determine whether the wave characteristic most closely related to sickness was a particular peak acceleration magnitude, a particular acceleration phase duration, or a particular time interval between accelerations.

The Wesleyan University studies of motion sickness were concluded with a study of the effects upon sickness rates of various wave frequencies but identical peak acceleration magnitudes (Alexander *et al.*, 1947). The study involved four conditions with constant velocity phase duration, constant peak acceleration magnitude but varying acceleration phase duration and varying peak velocity magnitude. For consistency between experiments, the wave frequencies varied between 0.22 and 0.53 cycles per second. Motion sickness decreased with increasing wave frequency and was significantly different with the lowest and highest wave frequencies. From a discussion of the results from the four studies (Alexander *et al.*; 1945a, 1945b, 1945c, 1947), the investigators concluded that the capacity of a wave to induce sickness depended on wave-duration, acceleration-level and energy per wave.

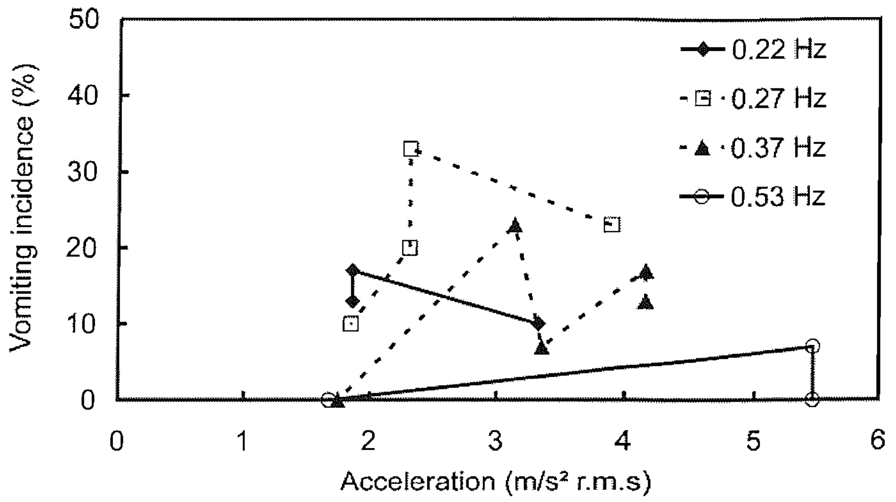

Figure 2.29 The effects of root-mean-acceleration at frequencies less than 1 Hz for four dominant frequencies of oscillation with 20-minute exposures (recreated using data from Alexander *et al.* 1947 and the methods of Lawther and Griffin, 1987).

The limitations in the control of the lift device used by Alexander confounded the effects of the variables frequency and acceleration magnitude. Spectral analysis of idealised motion waveforms was used by Lawther and Griffin (1987) to reinterpret the Wesleyan University data. By assuming the actual motions were well represented by the idealised waveforms, the data was summarised by calculating the dominant frequency and the root-mean-square acceleration at frequencies less than 1 Hz. In all cases the dominant frequency was the same as the wave frequency. The proportion of subjects vomiting is shown, as a function of the calculated root-mean-square acceleration magnitude and the dominant frequency, in Figure 2.29. For motions with constant wave frequency, the reanalysis suggested a tendency of increased vomiting with increased acceleration magnitude (Lawther and Griffin, 1987).

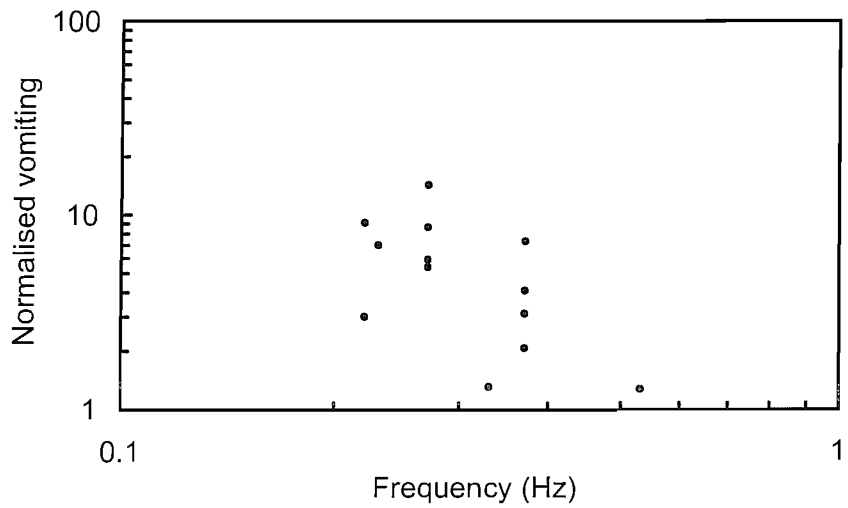

Figure 2.30 The effects of frequency on normalised vomiting incidence for 20-minute exposures (recreated using data from Alexander *et al.* 1947 and the methods of Lawther and Griffin, 1987).

Further reinterpretation of the Wesleyan University studies by Lawther and Griffin (Lawther and Griffin, 1987) determined the effect of wave frequency. The authors had established that the effect of the root-mean-square acceleration magnitude could be controlled by linear methods: for each condition, the frequency effect was sufficiently approximated by normalising the percentage of subjects who vomited by the root-mean-square acceleration magnitude. When plotted against frequency (Figure 2.30) the normalised vomiting incidence shows some scatter, although there is a trend of decreased sickness with increased frequency (Lawther and Griffin, 1987).

Human Factors, Inc. studies of vertical oscillation

A series of studies of vertical oscillation involving approximately 1000 subjects were undertaken by Human Factors Research, Inc. (O'Hanlon and McCauley, 1974; McCauley *et al.*, 1976). In these studies, subjects were exposed to up to 2 hours of sinusoidal vertical oscillation. The subjects sat in a cabin on a chair with a head support. Their eyes were open but they had no external view.

O'Hanlon and McCauley (O'Hanlon and McCauley, 1974) studied 14 conditions of vertical motion to investigate the effects on motion sickness of four oscillation frequencies (0.083, 0.167, 0.333 and 0.5 Hz) and six magnitudes (0.28, 0.55, 1.11, 2.22, 3.33, and 4.44 m/s^2 r.m.s). Independent groups of upwards of 20 subjects were exposed in each condition. The incidence of vomiting (designated motion sickness incidence or MSI) showed a monotonic increase with acceleration at each frequency of oscillation. The relationship between the frequency and the incidence of vomiting was thought to be complex; however the authors approximated the relationship as a quadratic function of oscillation frequency: with increasing frequency of oscillation, motion sickness tended to increase between 0.083 and 0.167 Hz and decrease between 0.167 and 0.5 Hz. No statistical analysis of the differences in motion sickness between conditions was reported. In conclusion, O'Hanlon and McCauley suggested that when compared to the work of Wendt *et al.* (1947), they found the same curvilinear relationship between the wave frequency and the vomiting incidence. They further concluded that with vertical periodic motion, the wave frequency is a critical factor for determining the response of the physiological mechanism responsible for motion sickness and maximum susceptibility seems to be in the region 0.2 Hz.

McCauley *et al.* (McCauley *et al.*, 1976) extended their study of vertical motion to include four conditions with various combinations of three frequencies (0.5, 0.6 and 0.7 Hz) and two magnitudes (4.5 and 5.5 ms^{-2} r.m.s). The results were consistent with their previous experiment, such that vomiting increased monotonically with increasing root-mean-square acceleration magnitude and decreased with increasing frequency.

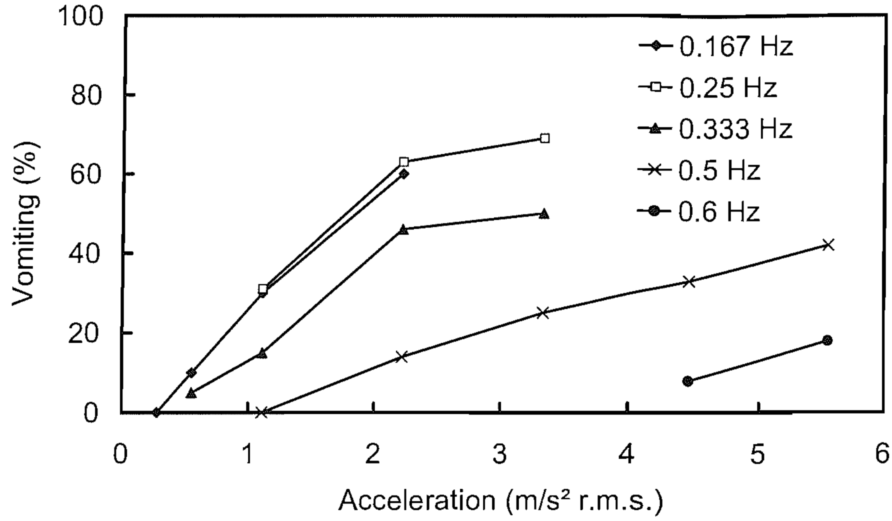

Figure 2.31 The effect of magnitude of 2-hour exposures for five frequencies of vertical oscillation (recreated using data O'Hanlon and McCauley, 1974, McCauley *et al.* 1976 and the methods of Lawther and Griffin, 1987).

The Human Factors Inc. data (O'Hanlon and McCauley, 1974; McCauley *et al.*, 1976) was treated by Lawther and Griffin (Lawther and Griffin, 1987) in a manner similar to the Wesleyan University data (Alexander *et al.*, 1947). For various frequencies of oscillation, vomiting incidence increased as a monotonic and approximately linear function of increasing acceleration magnitude (Figure 2.31).

By repeating the approximation that linear methods can be used to normalise the effect of root-mean-square acceleration magnitude, Lawther and Griffin (1987) calculated the normalised vomiting incidence for 2-hour exposures. Figure 2.32 shows a clear trend of decreasing normalised vomiting incidence with increasing frequency. Only one data point, at the lowest experimental frequency of 0.083 Hz, proved an exception to this trend.

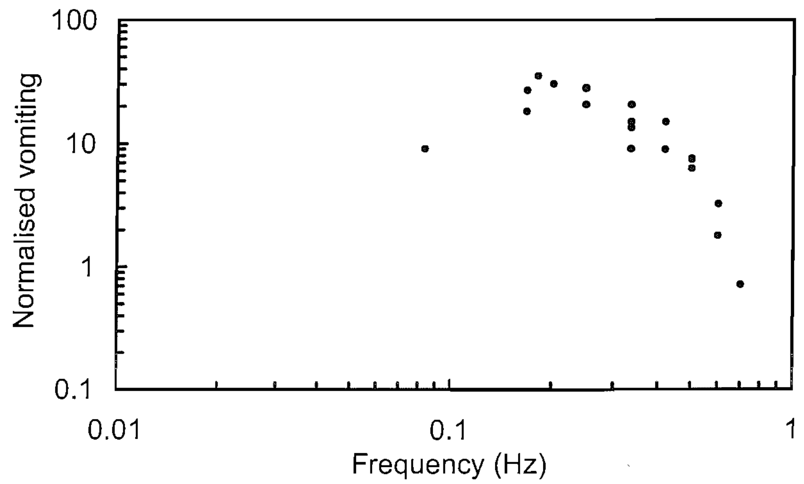

Figure 2.32 Effect of frequency on normalised vomiting incidence for 2-hour exposures to vertical oscillation (recreated using data O'Hanlon and McCauley, 1974, McCauley *et al.* 1976 and the methods of Lawther and Griffin, 1987).

Summary of the effects of vertical oscillation

Consistent and conclusive trends were observed in studies of the effects on motion sickness of the magnitude and frequency of vertical oscillation. Over the frequency range from 0.083 to 0.7 Hz, sensitivity to motion sickness was greatest around 0.2 Hz and vomiting incidence increased approximately linearly with increasing root-mean-square acceleration magnitude up to about 6 ms^{-2}. One data point at 0.083 Hz suggests that below 0.167 Hz motion sickness increases with increasing frequency but this finding is by no means conclusive.

2.10.3 Empirical models of motion sickness with vertical oscillation

Motion sickness incidence model

An original "motion sickness incidence (MSI) model" was proposed (O'Hanlon and McCauley, 1974; McCauley *et al.*, 1976) to describe the relationship between the frequency and magnitude of vertical oscillation and vomiting incidence. For each individual frequency, the authors assumed that motion sickness incidence varied as an ogival function (the cumulative normal distribution) of acceleration and time. In the MSI model, the percentage motion sickness incidence was expressed as product of a term representing the effect of acceleration and frequency, P_a, and a term dependent on duration, P_t (as summarised in Griffin, 1991):

$$\mathrm{MSI} = 100 \cdot P_a \cdot P_t$$

The terms P_a and P_t are probabilities found from the cumulative standard normal distribution for given values of the respective normal deviates z_a and z_t; z_a describes the effects of acceleration and frequency, and z_t describes the effect of exposure time. The equation for z_a was determined by fitting a curve required to produce vomiting at various frequencies in 50% of persons during two-hour exposures (as summarised in Griffin, 1991):

$$z_a = 2.13 \cdot \log_{10} a - 9.28 \cdot \log_{10} f - 5.81 \cdot (\log_{10} f)^2 - 1.85$$

Where a is the r.m.s acceleration in g; f is the frequency in Hz. The equation for z_t was calculated similarly to give (as summarised in Griffin, 1991):

$$z_t = 2 \cdot \log_{10} t + 1.13 \cdot z_a - 2.90$$

Where t is the exposure time in minutes.

MSI model predictions of vomiting incidence for a two-hour exposure are plotted in Figure 2.33 for a range of oscillation frequencies and acceleration magnitudes. Note that with this form of model, predictions of motion sickness cannot exceed 100%.

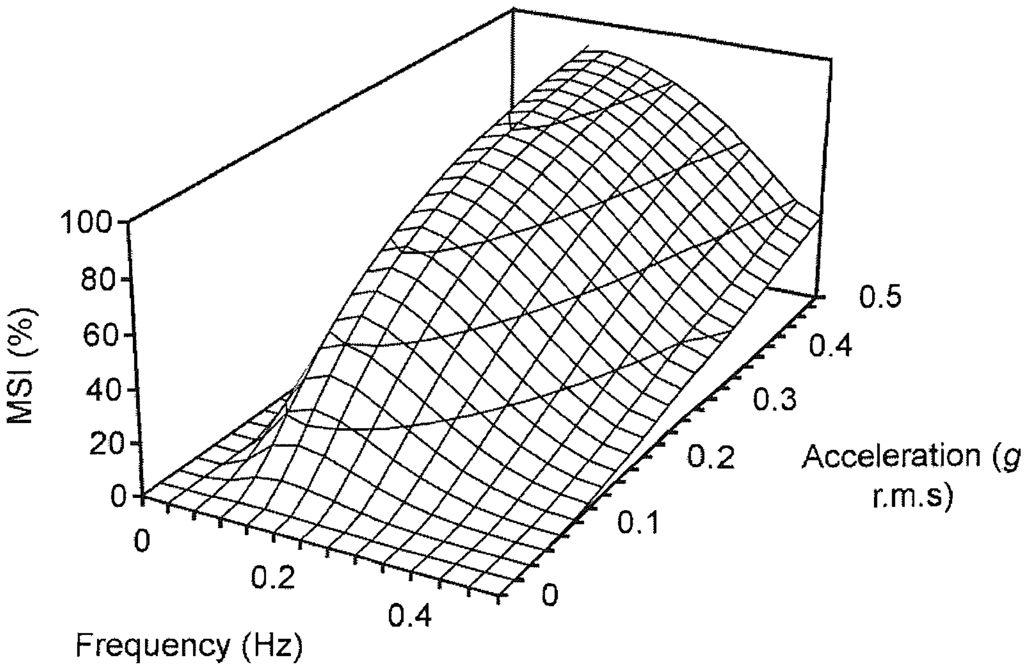

Figure 2.33 Motion sickness incidence (MSI) model, reproduced using the methods described by Griffin (1991).

Motion Sickness Dose Value model and W_f

Lawther and Griffin (1987) used normalised vomiting incidence data from the laboratory studies of Alexander *et al.* and McCauley *et al.* and from their own studies of seasickness to define an acceleration frequency weighting for vertical oscillation. The frequency weighting method was adopted by British Standard 6841:1987 (British Standards Institution, 1987) and International Standard 2631-1:1997 (International Organization for Standardization, 1997b), which define a fully realisable acceleration frequency weighting to be used in assessing low-frequency vertical motions with respect to motion sickness. The standardised acceleration frequency weighting is defined as W_f and is further described in Draft International Standard 8041:2005 (International Organization for Standardization, 2005) relating to “Human response to vibration – measuring instrumentation”.

The frequency weighting, W_f, is defined at all frequencies but is only intended to predict sickness in the range 0.1 – 0.5 Hz. Therefore in addition to the weighting a band-limiting filter is defined. The corner frequencies of the band limiting filter are one-third of an octave outside the frequency range over which the weighting is intended to predict sickness. The frequency weighting therefore has high and low-pass band-limiting filters at 0.08 and 0.63 Hz respectively.

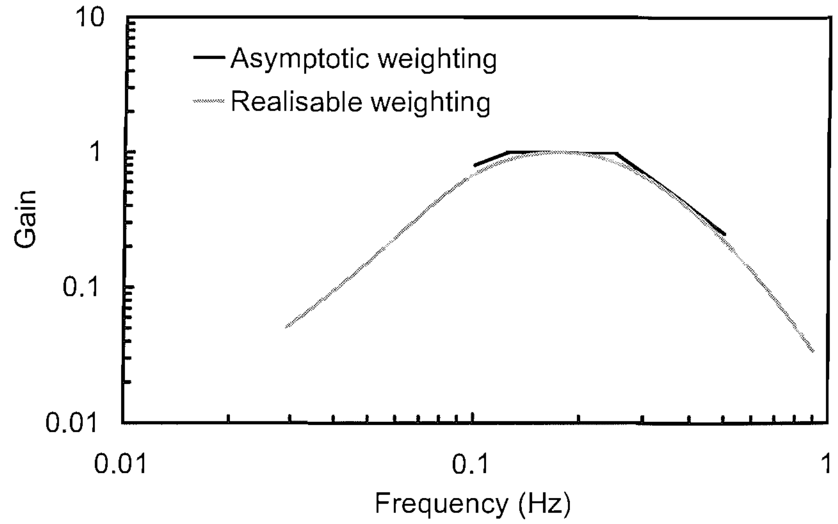

Figure 2.34 Frequency weighting W_f as defined in British Standard 6841 (1987). (Graph show straight lines 'asymptotic approximations' to the illustrated realisable weighting defined by the standard for use in instrumentation).

Asymptotic approximations[6] to the realisable frequency weighting have a slope of +6 dB per octave (proportional to velocity) at frequencies up to 0.125 Hz, 0 dB per octave (proportional to acceleration) in the range 0.125 to 0.25 Hz and −12 dB per octave (proportional to displacement) at frequencies above 0.25 Hz. The realisable and asymptotic alternatives to the frequency weighting W_f are shown Figure 2.34.

$$H_{W_f}(s) = K \cdot \frac{K \cdot \left(1 + \frac{s}{\omega_5 \cdot Q_5} + \frac{s^2}{\omega_5^2}\right)}{\left(1 + \frac{\omega_1}{s \cdot Q_1} + \frac{\omega_1^2}{s^2}\right)\left(1 + \frac{s}{\omega_2 \cdot Q_2} + \frac{s^2}{\omega_2^2}\right)\left(1 + \frac{s}{\omega_4 \cdot Q_4} + \frac{s^2}{\omega_4^2}\right)\left(1 + \frac{s}{\omega_6 \cdot Q_6} + \frac{s^2}{\omega_6^2}\right)} \cdot \frac{\omega_5^2}{\omega_6^2}$$

The expression defining the band-limited frequency weighting, as defined by DIS 8041:2005, is given above and the equation parameters are given in Table 2.6. When comparing the Draft International Standard and the British Standard, the definitions of the weighting expressions are not exactly equivalent. For equivalence, the weighting gain, K, in the British Standard should be 1.024; however the influence of the differences due to scaling will be small.

Table 2.6 Characteristics of the band-limiting and frequency weighting filters for frequency weighting W_f.

Band-limiting				Frequency weighting						
ω_1	ω_2	Q_1	Q_2	ω_4	ω_5	ω_6	Q_4	Q_5	Q_6	K
2·π·0.08	2·π·0.63	1/√2	1/√2	2·π·0.25	2·π·0.0625	2·π·0.1	0.86	0.8	0.8	1.0

[6] A rectilinear asymptote is considered a tangent to the curve produced to an infinite distance.

The incidence of motion sickness symptoms increases with increasing duration of motion exposure up to several hours. As well as defining an acceleration frequency weighting, Lawther and Griffin (Lawther and Griffin, 1987) also defined an acceleration motion "dose" procedure to evaluate the effect of duration on motion sickness. The British and International standards (BS 6841:1987 and ISO 2631-1:1997) also adopted the dose procedure to represent the relationship between sickness and frequency weighted acceleration magnitude on motion sickness, and defined the 'motion sickness dose value' ($MSDV_z$).

The $MSDV_z$, in metres per second to the power 1.5 ($ms^{-1.5}$), is given by the square root of the integral of the square of the *z*-axis acceleration after it has been frequency-weighted:

$$MSDV_z = \left\{ \int_0^T \left[a_w^2(t) \right] \cdot dt \right\}^{\frac{1}{2}}$$

Where $a_w(t)$ is the frequency-weighted acceleration in the *z*-direction and T is the total period (in seconds) during which motion could occur. This method is equivalent to calculating the root-mean-square value by true integration over the period T and multiplying by $T^{1/2}$.

If the motion exposure is continuous and of approximately constant magnitude, the $MSDV_z$ may be estimated from the frequency-weighted root-mean-square acceleration determined over a short period: such a $MSDV_z$ estimate is found by taking the product of the frequency-weighted root-mean-square *z*-axis acceleration, a_w, and the square-root of the exposure duration, T_0, in seconds (the measurement period should not normally be less than 240 s):

$$MSDV_z = a_w T_0^{1/2}$$

Assessments of the nauseogenicity of motion are then given by predictions of the percentage of un-adapted mixed male and female adults who may vomit; the following calculation is used:

$$\textit{percentage who may vomit} = \frac{1}{3} \times MSDV_z$$

The $MSDV_z$ is intended to be applied to exposures lasting from about 20-minutes to about 6-hours with a prevalence of vomiting up to 70%. It has been shown that for root-mean-square acceleration magnitudes up to 2.5 m/s^2 and for durations up to 6 hours, the dependency of the $MSDV_z$ and MSI models on frequency, acceleration and duration is similar (Lawther and Griffin, 1987). One uncertainty associated with the MSDV model for predicting motion sickness caused by vertical oscillation is the frequency-dependence of motion sickness at frequencies less than about 0.1 Hz.

2.10.4 Studies of motion sickness with horizontal translation

Farnborough studies of horizontal oscillation

Golding *et al.* reported successive investigations of the frequency effect on motion sickness of fore-and-aft oscillation (Golding and Markey, 1996; Golding, *et al.*, 1997; Golding, *et al.*, 2001). The experimental conditions were invariant between studies and in all studies a total of 12 subjects were exposed to horizontal oscillation, at one-week intervals, with order randomised between subjects. Throughout the experiments the subjects performed a visual search task and maintained an upright-seated posture with a headrest but no other head restraint. A Reason and Brand 'Motion Sickness Susceptibility Questionnaire' (Reason and Brand, 1975) was administered to each subject prior to participating in their first motion challenge.[7] Subjects rated their illness on a "revised" four-point sickness rating scale, as shown in Table 2.7. For each condition Golding documented the number of subjects reaching the moderate nausea endpoint, the mean time to reach the motion endpoint, and the mean symptom rating at the motion endpoint. These measures, along with others from subsequent studies are summarised in Table 2.8.

Table 2.7 Illness rating scales used by subjects during studies conducted by Golding *et al.* (Golding and Kerguelen, 1992; Golding *et al.*, 1995; Golding and Markey, 1996; Golding *et al.*, 1997; Golding *et al.*, 2001; Golding *et al.*, 2003).

Original scale		Revised scale	
Golding and Kerguelen, 1992		Golding *et al.*, 1995; Golding and Markey, 1996; Golding *et al.*, 1997; Golding *et al.*, 2001; Golding *et al.*, 2003	
Rating	Corresponding symptoms	Rating	Corresponding symptoms
1	No symptoms	1	No symptoms
2	Any symptoms however slight	-	-
3	Mild symptoms, e.g., stomach awareness but no nausea	2	Initial symptoms
4	Mild nausea	-	-
5	Mild to moderate nausea	3	Mild nausea
6	Moderate nausea (can continue)	-	-
7	Moderate nausea (stop motion)	4	Moderate nausea (stop motion)

[7] The questionnaire is used to calculate a score; a single measure of the susceptibility of a subject. The score is converted to a percentile score such that the mean percentile score of the 'normal' population would be expected to be 50%.

Table 2.8 Chronological summary of Golding *et al.* studies of motion sickness with low-frequency sinusoidal translational oscillation.

Study	Motion	Duration of exposure	N	MSSQ Percentile (%)	Motion condition	Head -body axis	Sickness measurement		
							N reaching moderate nausea	Mean time to motion endpoint	Symptom scores
Golding & Kerguelen (1992)	0.3 Hz; ±0.70 m; 1.8 ms^{-2} r.m.s.	45 min or moderate nausea endpoint	12	64.2	A. Horizontal – supine (eyes closed) B. Horizontal – supine (search task) C. Vertical – upright (eyes closed) D. Vertical – upright (search task)	z z z z	1/12 2/12 6/12 8/12	43.83 min 41.75 min 32.04 min 28.17 min	2.92 4.67 5.00 6.25
Golding, Markey & Stott (1995)	0.35 Hz; ±0.74 m; 2.55 ms^{-2} r.m.s.	30 min or moderate nausea endpoint	28 A-B 12 C-E	74.50 (A-B) 53.25 (C-E)	A. Horizontal –upright B. Vertical –upright C. Horizontal –upright D. Vertical –upright E. Vertical –supine	x z x z x	28/28 18/28 10/12 6/12 7/12	07.99 min 17.56 min 15.63 min 23.89 min 18.83 min	12.46 9.81 9.54 7.88 7.71
Golding & Markey (1996)	2.55 ms^{-2} r.m.s.	30 min or moderate nausea endpoint	12	59.4	A. Horizontal 0.205 Hz; ± 2.17 m B. Horizontal 0.35 Hz; ± 0.74 m C. Horizontal 0.50 Hz; ± 0.36 m	x x x	11/12 9/12 8/12	08.27 min 11.70min 21.03 min	12.54 11.42 9.79
Golding, Finch & Stott (1997)	2.55 ms^{-2} r.m.s.	30 min or moderate nausea endpoint	12	41.4	A. Horizontal 0.35 Hz; ± 0.74 m B. Horizontal 0.50 Hz; ± 0.36 m C. Horizontal 0.70 Hz; ± 0.19 m D. Horizontal 1.00 Hz; ± 0.09 m	x x x x	9/12 3/12 0/12 2/12	17.37 min 26.00 min 30.00 min 28.33 min	11.21 5.25 1.46 2.71
Golding, Mueller & Gresty (2001)	0.71 ms^{-2} r.m.s.	30 min or moderate nausea endpoint	12	86.4 (revised scoring)	A. Horizontal 0.10 Hz; ± 0.74 m B. Horizontal 0.20 Hz; ± 0.74 m C. Horizontal 0.40 Hz; ± 0.74 m	x x x	8/12 12/12 7/12	17.70 min 10.23 min 22.29 min	7.08 10.58 6.67

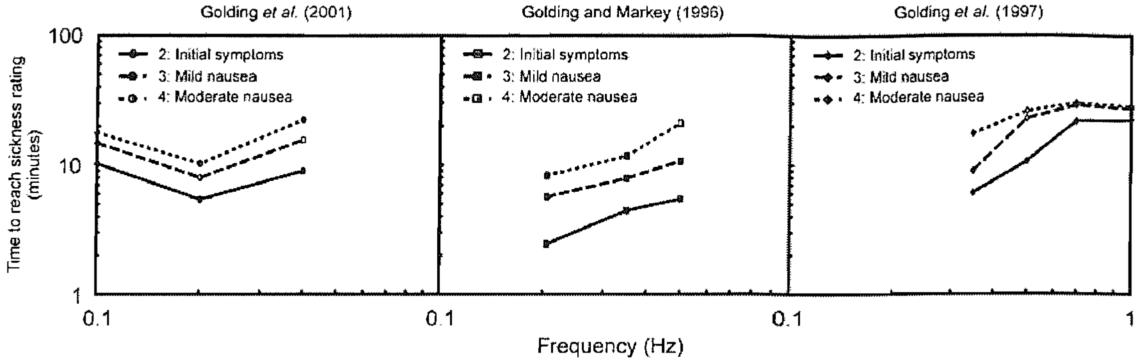

Figure 2.35 The effect of fore-and-aft oscillation frequency on the time to reach various stages of sickness.

With peak acceleration magnitudes of 3.6 ms^{-2}, Golding and Markey (Golding and Markey, 1996) studied fore-and-aft oscillation at frequencies ranging from 0.205 to 0.5 Hz. When rated using their motion sickness susceptibility questionnaire, the subjects (7 male; 5 female) had motion sickness susceptibilities representative of the normal population (mean percentile score = 59.4%). In the second experiment with the same peak acceleration magnitudes, Golding, Finch and Stott (Golding, *et al.*, 1997), studied fore-and-aft motion at frequencies in the range from 0.35 to 1.0 Hz. On this occasion the subjects (7 male; 5 female) had motion sickness susceptibilities slightly less than those might be expected from the normal population (mean percentile score = 41.4%). A third study (Golding, *et al.*, 2001) examined fore-and-aft oscillations at three frequencies spaced at octave intervals across the range from 0.1 to 0.4 Hz. Due to the displacement limits of the motion simulator (a sled), a lower 1.0 m/s^2 peak acceleration magnitude was necessary to realise the motions. Highly susceptible subjects, 6 male and 6 females (mean percentile score = 86.4%), were used to compensate for the potential lack of nauseogenicity of the motions due to a reduced acceleration magnitude.

In the Golding *et al.* studies, the sickness measure of interest was the mean time taken by subjects to reach a given sickness rating. For each condition the "log back transformed" mean time to sickness was calculated to satisfy assumptions for statistical analysis using ANOVA. Figure 2.35 plots for each study and for each 'non-zero symptom' sickness rating the mean time taken to reach each sickness rating as a function of frequency.

With increasing oscillation frequency above 0.2 Hz, the studies of Golding *et al.* consistently found that the incidence of subjects reaching moderate nausea significantly decreased, whilst the mean time to reach each sickness rating significantly increased. With oscillation below 0.2 Hz, the mean time to reach moderate nausea significantly decreased with increasing oscillation frequency (Golding *et al.*, 2001). It was concluded that, as with vertical oscillation, there is a peak in the motion sickness response in the region of 0.2 Hz. These findings are reflected in Figure 2.35. The figure also reflects other influences: i) relative to the conditions with similar oscillation frequencies but with 3.6 m/s^2

peak acceleration magnitudes (Golding and Markey, 1996; Golding *et al.*, 1997), the time to reach each sickness rating was longer in the study involving the lowest, 1.0 m/s², peak accelerations (Golding *et al.*, 2001); ii) with similar acceleration magnitudes and oscillation frequencies, subjects with lower motion sickness susceptibilities (Figure 2.35, third panel) took longer to reach each sickness rating than subjects with higher susceptibilities (Figure 2.35, second panel); iii) with the least nauseogenic oscillations (e.g. oscillation at 1.0 Hz; Figure 2.35, third panel) there was a downward bias in the time to reach each sickness rating as not all the subjects reached all the ratings prior to the motion end-point (after 30 minutes).

For each study the authors evaluated their data using a dose model procedure suggested for vertical oscillation (Lawther and Griffin, 1987). The dose model predicts the proportion of exposed subjects reporting a given illness (or sickness) rating, *P*, from the frequency weighted, *W(f)*, root-mean-square acceleration, a_{rms}, and the duration of exposure, *t*:

$$P = K \cdot W(f) \cdot a_{rms} \cdot t^{1/2}$$

The value of *K* depends on the motion sickness measure of interest. The model was derived for exposure durations ranging from 20-minutes to 6-hours and assumes that motion sickness increases in proportion to the square-root of the duration.

In each of their studies, Golding *et al.* used the dose model to calculate weighting values to assess the effect of frequency with 30-minute exposures to fore-and-aft oscillation. Using various sickness ratings and various frequency ranges, the slopes of the weightings were estimated: for 0.205 to 0.5 Hz, the frequency weighting slope based on moderate nausea was estimated as -3.7 dB/octave; for 0.35 to 0.7 Hz, a -5.5 dB/octave slope represented the times to initial symptoms; for 0.35 to 1 Hz, a -4.5 dB/octave slope was estimated based on sickness ratings on the 1-4 scale at motion endpoint; for 0.2 to 0.4 Hz a slope for moderate nausea ranging from -2.56 to -4.00 dB/octave was thought appropriate; and for 0.1 to 0.2 Hz the slope for moderate nausea was estimated to be between 2.05 and 3.06 dB/octave.

It was suggested that the nauseogenicity of fore-and-aft oscillation was greater than that predicted by the dose model. Furthermore, the estimated slopes for sickness appeared less steep than those defined by the W_f frequency weighting. The disparities may be due to the following: differences in susceptibility to motions in these axes or the differences in the measures used to define the frequency weightings. It is also noted that Golding *et al.* used the dose model, which takes the square-root of the exposure time, to calculate the weighting; however, the 30-minute experimental duration was only slightly greater than 20-minute limit of dose model applicability. In this case, it is possible that the duration effect on motion sickness was not well modelled by the dose model and the frequency weighting slope estimates biased: when a linear model was used the predicted slopes were closer to those predicted by the W_f frequency weighting.

Institute of Sound and Vibration Research studies of horizontal oscillation

A series of experiments investigating the effects on motion sickness of the frequency, magnitude and direction of horizontal oscillation was conducted at the Institute of Sound and Vibration Research within the University of Southampton. The motion axes, frequencies and acceleration magnitudes are summarised in Table 2.9. During these motion conditions subjects sat on a rigid chair with a low backrest, no headrest, and no external view. Subjects were exposed for up to 30 minutes and were asked to rate their illness at one-minute intervals using a seven-point illness rating scale. Table 2.9 summarises for each motion condition the number of subjects reporting each non-zero illness rating and the mean accumulated illness rating.[8]

An experiment involving 168 subjects studied the frequency effects on motion sickness of fore-and-aft and lateral oscillations (Griffin and Mills, 2002a). With constant peak velocity oscillations (0.5 ms^{-1}) and 7 frequencies over the range of 0.2 to 0.8 Hz, there were no significant effects of frequency or motion direction. It was suggested that with horizontal oscillation over the range 0.2 to 0.8 Hz, motion sickness is very approximately dependent on the peak velocity of oscillation. An acceleration frequency weighting having a gain inversely proportional to frequency was suggested as providing a simple method of evaluating this type of motion in transport; however, the results also suggest that a more complex weighting might be required.

The effect on motion sickness of lateral and fore-and-aft oscillation magnitude was studied in an experiment involving 144 subjects and 12 conditions (Griffin and Mills 2002b). Constant frequency oscillations at 0.315 Hz were used to study 6 root-mean-square acceleration magnitudes over the range 0.0 to 1.11 ms^{-2}. With either fore-and-aft or lateral oscillation, there was a trend of increasing sickness with increasing magnitude; however, within each axis of motion, paired comparisons of the magnitude conditions revealed only one significant difference. The direction of motion did not produce significant differences in motion sickness.

A study of the effect of seating, vision and direction of horizontal oscillation on motion sickness (Mills and Griffin, 2000) revealed two other motion conditions relevant to this review. With subjects sat with a low backrest and their eyes open, a comparison of motion

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[8] The table consists of published data and unpublished data, which for the purposes of this review has been gathered from re-analysis of the raw data available within the Institute of Sound and Vibration Research.

sickness with oscillations at 0.25 Hz and 0.7 m/s² root-mean-square found significantly more sickness with fore-and-aft oscillation than with lateral oscillation.

Table 2.9 Summaries of the motion and motion sickness data obtained in published and unpublished studies of horizontal and vertical oscillation conducted by Mills and Griffin at the Institute of Sound and Vibration Research. IR_Σ represents the mean accumulated illness rating (N_1, N_2 ... N_6, represent the numbers of subjects reporting each illness rating, as indicated by the subscript).

Study	Axis	*f* (Hz)	*a* (m/s² r.m.s)	N_{total}	Number of subjects reporting illness rating						IR_Σ
					N_1	N_2	N_3	N_4	N_5	N_6	
Mills and Griffin (2000)	*x*	0.25	0.7	12	10	9	7	5	4	3	62.6
	y	0.25	0.7	12	9	8	5	3	1	1	43.8
Griffin and Mills (2002a)	*x*	0.2	0.44	12	11	6	3	3	3	1	28.8
	y	0.2	0.44	12	10	4	4	3	2	1	32.3
	x	0.25	0.56	12	10	8	1	0	0	0	25.7
	y	0.25	0.56	12	9	7	4	4	4	3	46.5
	x	0.315	0.7	12	9	7	5	5	4	2	40.6
	y	0.315	0.7	12	11	8	6	4	2	1	41.5
	x	0.4	0.89	12	9	5	4	2	2	2	35.8
	y	0.4	0.89	12	9	7	2	1	0	0	28.8
	x	0.5	1.11	12	10	6	4	1	0	0	26.0
	y	0.5	1.11	12	7	6	2	2	0	0	24.0
	x	0.63	1.33	12	11	6	4	3	1	0	38.7
	y	0.63	1.33	12	9	6	2	0	0	0	17.1
	x	0.8	1.78	12	8	6	3	2	1	0	28.0
	y	0.8	1.78	12	9	4	2	2	0	0	24.3
Griffin and Mills (2002b)	*x*	0	0	12	5	2	1	0	0	0	8.3
	y	0	0	12	8	1	0	0	0	0	9.8
	x	0.315	0.28	12	9	5	2	1	1	0	26.0
	y	0.315	0.28	12	9	5	2	1	0	0	21.3
	x	0.315	0.56	12	9	4	4	3	1	1	34.8
	y	0.315	0.56	12	9	6	3	2	2	1	35.4
	x	0.315	0.7	12	10	4	3	2	2	2	39.7
	y	0.315	0.7	12	9	7	2	0	0	0	25.4
	x	0.315	0.89	12	11	10	6	5	4	3	58.1
	y	0.315	0.89	12	6	3	2	1	0	0	18.3
	x	0.315	1.11	12	11	8	7	3	1	1	43.0
	y	0.315	1.11	12	11	6	6	5	0	0	36.7
Mills and Griffin (Unpublished)	*y*	0.25	0.22	20	18	9	2	2	1	1	24.3
	y	0.25	0.44	20	19	10	2	2	1	1	28.2
	z	0.25	0.22	20	18	10	5	1	0	0	28.9
	z	0.25	0.44	20	18	13	6	5	3	3	41.1

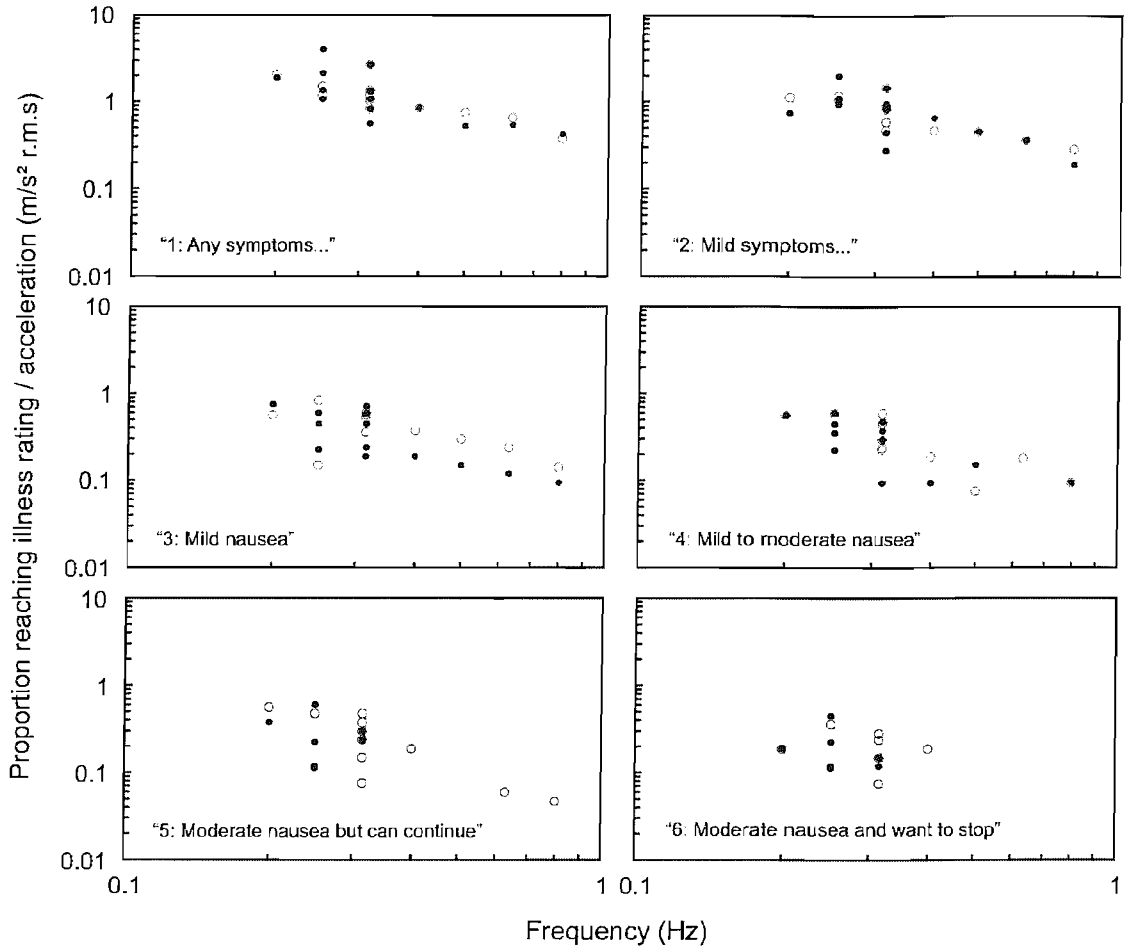


Figure 2.36 Proportion of subjects reporting each illness rating divided by the root-mean-square acceleration magnitude, shown for lateral (solid points) and fore-and-aft (open rings) oscillation. Values calculated from published and unpublished data obtained during studies conducted at the Institute of Sound and Vibration Research (Mills and Griffin, 1998; Griffin and Mills, 2002a; Griffin and Mills, 2002b).

The data from the ISVR studies of horizontal oscillation (summarised in Table 2.9) can be reanalysed using the techniques suggested by Lawther and Griffin (Lawther and Griffin, 1987) for vertical oscillation. For these studies subjects did not vomit and so a normalised vomiting procedure is not appropriate. An alternative procedure would normalise the proportion of subjects reporting each illness rating by the root-mean-square acceleration magnitude. For both fore-and-aft and lateral oscillations, Figure 2.36 plots the normalised proportion of subjects reaching each illness rating as a function of frequency. The figure shows consistent trends of decreasing sensitivity with increasing frequency.

Summary of the effects of horizontal oscillation

Consistent and conclusive trends were observed in studies of the effects on motion sickness of the magnitude and frequency of horizontal oscillation. Over the frequency range from 0.2 to 0.8 Hz, sensitivity to motion sickness was greatest around 0.2 Hz. Motion sickness increased with increasing root-mean-square acceleration magnitude. One data point at 0.1 Hz suggests that below 0.2 Hz motion sickness increases with increasing frequency but there is little data to fully support such a conclusion.

2.10.5 Studies comparing motion sickness with vertical and horizontal translation

Early analyses of the causes of motion sickness were apparently aware that posture and the direction of motion had a role in the development of motion sickness: Irwin (1881) stated that it was a "well-known fact that sea-sickness is least felt in the recumbent posture, with the head low and the feet towards the stern".

To determine the effect of posture on motion sickness, Golding and Kerguelen compared the nauseogenic potential of low-frequency translational motion in the Earth-vertical plane and the Earth-horizontal plane when delivered through the same *z*-axis of the head and body (Golding and Kerguelen, 1992). Although the imposed head-body *z*-axis forces were equivalent for the two conditions (0.3 Hz, 1.8 ms^{-2} r.m.s and ±0.7 m), the resultant gravito-inertial force vector differed due to the changed orientation of the translational acceleration with respect to gravity. The 12 subjects (9 males, 3 females) were exposed to four motion challenges with at least 6 days between exposures: they repeated the two motion conditions, once whilst performing a visual search task and again whilst keeping their eyes closed. The subjects rated the extent of their illness every minute using a seven-point scale (Table 2.7) and the exposure was terminated when a subject reached an illness rating of 7 or after 45 minutes of exposure. The mean percentile score for the subjects was 64.2% indicating a higher susceptibility of the group compared to the normal population. With the direction of the imposed oscillation in the z-axis of the head-body, the authors stated that vertical motion was highly significantly more provocative than horizontal motion, and nauseogenicity of the motion was exacerbated by a visual search task.

Golding offered the possible explanation that the observed motion sickness resulted from low frequency variations in the absolute magnitude of the resultant force vector as opposed to changes in its direction, thus the change in the absolute magnitude of the resultant force was smaller for horizontal motion than for vertical motion. A possible alternative was that the supine posture might reduce the nauseogenicity of the low frequency linear oscillation as it decreased the necessity for postural control when compared to the upright-seated posture. The effect of the visual condition (eyes closed, or search task) on motion sickness was independent of motion and the visual-vestibular mismatch evoked by the search task was said to enhance the effects of an intra-vestibular mismatch produced by low frequency oscillatory motion.

Table 2.10 Summaries of conditions comparing the relative nauseogenicity of horizontal and vertical oscillation and the effect of posture (from: Golding, Markey and Stott, 1995).

Condition	Earth-acceleration	Subject-acceleration	Posture	Ratio of time to Nausea
A	*x*	*x*	Upright	1.8 – 2.5
B	*z*	*x*	Supine	1.2
C	*z*	*z*	Upright	1.0
D	*x*	*z*	Supine	0.5

Golding *et al.* (Golding *et al.*, 1995) subsequently performed two experiments to distinguish the influences on motion sickness of the direction of motion, the orientation of motion with respect to the body, and the effect of posture. In this study the subjects used a "revised" four-point illness rating scale to rate their motion sickness symptoms. The relationship of the revised scale to the original scale (Golding and Kerguelen, 1992) is shown in Table 2.7. The authors first compared the relative nauseogenicity of vertical and horizontal oscillation with an upright, seated, posture using 28 subjects with greater than normal motion sickness susceptibility. The second experiment involved 12 normally susceptible subjects (mean percentile score = 53.25%) repeating the comparison but with an additional condition involving supine exposure to vertical oscillation. A summary of the ratio of time to nausea for the various conditions of horizontal and vertical oscillation and posture is given in Table 2.10.

Horizontal oscillation in an upright posture provoked nausea significantly earlier than vertical oscillation in an upright posture. This contrasts with the previous finding of increased nausea with vertical oscillation in an upright posture compared to horizontal oscillation in a supine posture (Golding and Kerguelen, 1992). Supine vertical oscillation was less nauseogenic than horizontal upright oscillation and slightly more nauseogenic than upright vertical oscillation, although the differences were not significant. The dominant factors influencing motion sickness appeared to be the orientation of motion with respect to the subject (with *x*-axis oscillation more nauseogenic than *z*-axis oscillation) and posture (with a supine position affording subjects some protection from motion sickness), with these effects appearing additive.

Golding used these results to refute the earlier conclusion that the critical nauseogenic factor was the behaviour of the absolute resultant acceleration vector during oscillatory motion, as the effect of a change in body orientation, e.g. from upright to supine, which cannot affect the resultant, produces a reversal in relative nauseogenicity of vertical and horizontal motion. The authors noted the suggestion that a supine posture might decrease motion sickness because the requirement for postural control decreases. When relating the mathematical models of motion sickness based on horizontal and vertical oscillation Golding suggested that horizontal (fore-and-aft) motion was almost exactly twice as nauseogenic as vertical motion at the same frequency and magnitude.

An unpublished study (Mills and Griffin, 1998) compared the relative effects on motion sickness of vertical and lateral oscillation with two root-mean-square acceleration magnitudes (0.22 and 0.44 m/s²). For each of the four conditions investigated, the motions and resultant motion sickness are summarised in Table 2.9. With both lateral and vertical oscillations, higher magnitudes of acceleration tended to cause more motion sickness than lower magnitudes. Statistical analysis of the accumulated illness ratings reported by subjects revealed that differences due to changes in the acceleration magnitude and direction of oscillation were insignificant. Cox regression modelling of the influence of the magnitude and direction on the time to reach mild nausea suggested that over the investigated range of root-mean-square accelerations, the magnitude of motion was not a significant covariate; however, subjects were approximately four times more likely to report mild nausea with vertical oscillation than with lateral oscillation.

In summary, it appears that translational oscillation in the vertical direction is more nauseogenic than in the lateral direction; however the effect requires further investigation over a greater range of frequencies and acceleration magnitudes.

2.10.6 Studies of motion sickness with oscillatory rotation about horizontal axes

There have been few studies of motion sickness with pure rotation (no translation) about a horizontal axis. Studies reporting conditions of pure roll or pure pitch rotation have tended to compare these conditions to motion sickness with simultaneous translation and rotation. As such little is known about the precise influence on motion sickness of the magnitude and frequency of pitch and roll oscillations. Where appropriate, studies reporting the motion sickness response to oscillatory rotation about subject head-referenced horizontal axes are also included.

In order to refine their MSI model (Section 2.10.3), McCauley *et al.* (1976) studied the effect of 2-hour exposures to pure pitch and roll oscillations. No subjects vomited with pure roll motion (N = 21) (33.3 °/s² at 0.345 Hz) but two subjects vomited (N = 22) with the same magnitude and frequency of pure pitch rotation. The incidence of vomiting was significantly lower than that reported with pure vertical oscillation (31%) at 0.25 Hz and a root-mean-square acceleration magnitude of 0.11 g.

By assuming a common underlying mechanism, one study compared changes in vestibular-ocular reflex dynamics and motion sickness with various axes of semicircular canal stimulation (Guedry *et al.*, 1990). A total of 75 subjects were exposed to sinusoidal yaw oscillation at 0.04 Hz with a peak velocity of ± 120 degrees/s. The subjects participated in one of five conditions investigating the effects of various orientations and postures with respect to rotations about a yaw axis (i.e. the Earth-vertical *z* axis), described as follows: 1) with a 90 degree whole-body tilt about the Earth-horizontal fore-and-aft (*x*) axis, the subject's interaural (*y'*) axis was aligned with the Earth-vertical yaw axis, thus the subject's vertical canals (sensitive to rotations about the subjects *x'* and *y'* axes) were stimulated in pitch and their horizontal canals (sensitive to rotations about the subjects z' axis) were minimally stimulated; 2) with subjects seated upright but their heads pitched 20 degrees downwards[9], stimulation to the subjects' horizontal and vertical semicircular canals respectively was maximised and minimised; 3) with subjects otherwise sat upright, but their heads rotated leftwards 90 degrees and then tilted 90 degrees downwards, their interaural axis was aligned with the centre of yaw rotation. The canal stimulation was equivalent to the first condition but, unlike that condition, "*g*-gradients on the lower body were minimised"; 4) Subjects kept a normal upright posture but underwent a 30 degree upwards pitch to put them in a semi-face-up position. The horizontal canals were then 50 degrees from the plane of rotation such that they had approximately equivalent stimulation to the vertical canals; 5) the previous condition was repeated, but with a 60 degree upward pitch such that the horizontal canals were 80 degrees from the plane of rotation. In this position, the vertical canals were stimulated strongly in roll, whilst the horizontal canals were stimulated weakly. The signs and symptoms of motion sickness were virtually negligible in group 2), slight in group 4) and clearly present in groups 1), 3) and 5). When tested across all groups, the differences were significant. Although dependent on the motion sickness measure, paired comparisons showed that groups 1), 3) and 5) tended to cause significantly more illness than conditions l) and 2). Similarly, group 4) caused more illness than group 1). The authors concluded that motion sickness appeared to be related to the amount of vertical semicircular canal stimulation received with no clear difference between roll-axis and pitch-axis groups.

In a 'control study' of pure roll oscillation, Wertheim *et al.* (Wertheim *et al.*, 1998) concluded that roll motions by themselves had no motion sickness-inducing potential: with roll oscillation at 0.1 Hz and root-mean-square displacements in the range 7.1 to 9.9°, motion sickness scores 'remained very low' over a two-hour exposure period, although one subject (N = 27) did quit from being close to vomiting. A subsequent condition was used to investigate motion sickness with pitch rotations and roll rotations when combined such that their phases and amplitudes were equivalent. With the combined motion, one subject (N = 30) quit (being close to vomiting) and one subject come close to vomiting,

---

[9] The angle of 20 degrees is determined by aligning a line, drawn through the outer canthus to the tragus, with the Earth-horizontal.

although 'on average' scores remained very low. The authors concluded that "irrespective of whether pitch and roll are present separately or in combination, they only have a small potential to generate motion sickness." However, no statistical analyses were provided, or indeed possible, to support their conclusions.

Förstberg (Förstberg, 1999) compared various conditions of lateral and roll oscillation with motion waveforms consisting of a periodic pattern of various motion events representative of those experienced in tilting-trains. With approximately equivalent lateral acceleration magnitudes (due to either lateral acceleration or the component of gravity due to roll), motion sickness with pure roll oscillation was less than with pure lateral oscillation and much less than that with combined lateral and roll oscillation.

In response to the paucity of data identifying the magnitude and frequency effect on motion sickness, Howarth and Griffin studied 5 conditions of roll oscillation using the same roll angle (8 degrees) over the frequency range 0.025 Hz to 0.40 Hz (Howarth and Griffin, 2003). The reported motion sickness data are summarised in Table 2.11. Roll motions appeared to cause little motion sickness[10] and there were no significant differences in motion sickness over the five conditions. The authors suggested that, with these motions, motion sickness might be dependent on the roll angle; although, as the centre of roll was at the seat surface and not at the head it was possible that the lateral head motion caused by roll motion of the seat combined with the roll motion of the head to either enhance or inhibit the symptoms of motion sickness. It was concluded that sickness caused solely by roll oscillation will usually be less than the motion sickness associated with translation oscillation or with translational oscillation combined with roll oscillation.

Table 2.11 Summary of motion sickness data reported with pure roll oscillation (Howarth and Griffin, 2003). IR_Σ represents the mean accumulated illness rating (unpublished data – calculated from the raw data available at the University of Southampton).

Study	f (Hz)	φ (peak, degrees)	N_{total}	Number of subjects reporting illness rating						IR_Σ
				N_1	N_2	N_3	N_4	N_5	N_6	
Howarth and Griffin (2003)	0.025	± 8	20	12	5	2	0	0	0	18.6
	0.05	± 8	20	19	5	2	1	0	0	23.1
	0.1	± 8	20	18	2	1	0	0	0	17.4
	0.2	± 8	20	17	8	3	1	1	1	18.9
	0.4	± 8	20	15	6	3	0	0	0	19.8

[10] e.g. in comparing the accumulated illness rating reported with roll oscillation (Table 2.11) to those reported with lateral oscillation (Table 2.9).

The studies reported above strongly suggest that rotational oscillations about horizontal axes are not particularly nauseogenic. The reviewed evidence suggests that there is little difference in motion sickness with pure roll and pure pitch oscillation; however further comparisons are necessary. When motion sickness with roll oscillation is observed, motion sickness may be dependent on the roll angle.

2.10.7 Studies of motion sickness with combined translation and rotation

Morton *et al.* (Morton *et al.*, 1947) used a 'roll-pitch rocker' to allow subjects to be exposed to a combined pitch and vertical motion, resulting from 'see-saw' motion through 3.6 metres, and simultaneous roll through 25.5 degrees. Combined vertical and pitch oscillation at 0.125 Hz resulted in 40% of subjects vomiting, whereas when the motion was combined with roll at 0.08 Hz, 33% of subjects vomited. As illness rates were similar with and without roll motion, the authors concluded that vertical motion from the seesaw was the cause of the sickness and that roll motion did not induce motion sickness.

When combined with 0.25 Hz vertical oscillation at a root-mean-square magnitude of 1.1 m/s^2 r.m.s., McCauley *et al.* investigated the response to pitch and roll oscillation at frequencies of 0.115, 0.230 or 0.345 Hz with root-mean-square magnitudes in the range 5.5 to 33.3 $degrees/s^2$ (McCauley *et al.*, 1976). The overall mean motion sickness incidence for pitch and vertical conditions was 34% and for the roll and vertical conditions, 31% and the differences were not significant. McCauley *et al.* concluded that the main cause of motion sickness in their experiment was vertical motion.

Wertheim argued that, although typical of the type of motion found on large passenger ships, the heave motion employed by McCauley *et al.* may have been sufficiently large to result in a masking effect of the relatively small pitch and roll motions (Wertheim *et al.*, 1998). Wertheim studied motions relevant to small high speed sea-borne craft by using pitch and roll oscillations, at frequencies between 0.03 and 0.17 Hz and rotational displacements between ±7° and ±14°, with and without 0.1 Hz vertical oscillation at amplitudes in the range 35 to 45 cm. With these rotation conditions, more sickness occurred with vertical oscillation than without. Between 3 and 26 subjects were exposed to each motion condition; however, as the conditions were presented longitudinally (i.e. consecutively) over 6 hours, the exposure durations varied significantly and no statistical analysis could be conducted. It was suggested that, when combined with small vertical oscillations, that in themselves, did not provoke motion sickness, the influence of roll and pitch oscillation was indeed important. The authors concluded that any model of motion sickness should combine "non-linearly" the separate effects of vertical, pitch, and roll motion.

When comparing low frequency motions in the translational and rotational axes within tilting-trains, lateral and roll oscillations tend to have the highest magnitudes. Förstberg studied various combinations of lateral and roll oscillation to investigate the causes of motion sickness in tilting-trains (Förstberg, 1999). A horizontal motion simulator produced motion waveforms consisting of a periodic pattern of various motion events representative of those experienced in tilting-trains. Seven conditions were employed to study various combinations of three peak lateral acceleration magnitudes, ranging from 0 to ± 1.1 m/s², and four peak roll displacements, ranging from 0 to ± 6.4°. The lateral and roll motions were always in phase. With the ± 1.1 m/s² peak Earth-horizontal acceleration combined with each of the four roll conditions, the lateral accelerations experienced by subjects were compensated by 0, 56, 75 and 100%. When combined with roll oscillation at the two intermediate peak displacements, ± 3.6°, ± 4.8°, the intermediate magnitude of lateral acceleration, ± 0.825 m/s², was compensated by 75 and 100%. With no lateral acceleration, the subjects experienced roll oscillation at ± 6.4° peak. A total of 42 male and female subjects participated in the study, 20 of whom completed all seven conditions, with the others completing between one and 5 conditions. The estimated mean nausea ratings at the 26th minute of motion exposure are shown in Figure 2.37. Monotonic increases in nausea rating were observed with increasing roll-compensation or increasing Earth-lateral acceleration magnitude. There were more reports of motion sickness with combined lateral and roll oscillation than with either lateral or roll oscillation alone. Within the waveform, the motion amplitudes and frequencies varied and their precise influence on motion sickness was unreported.

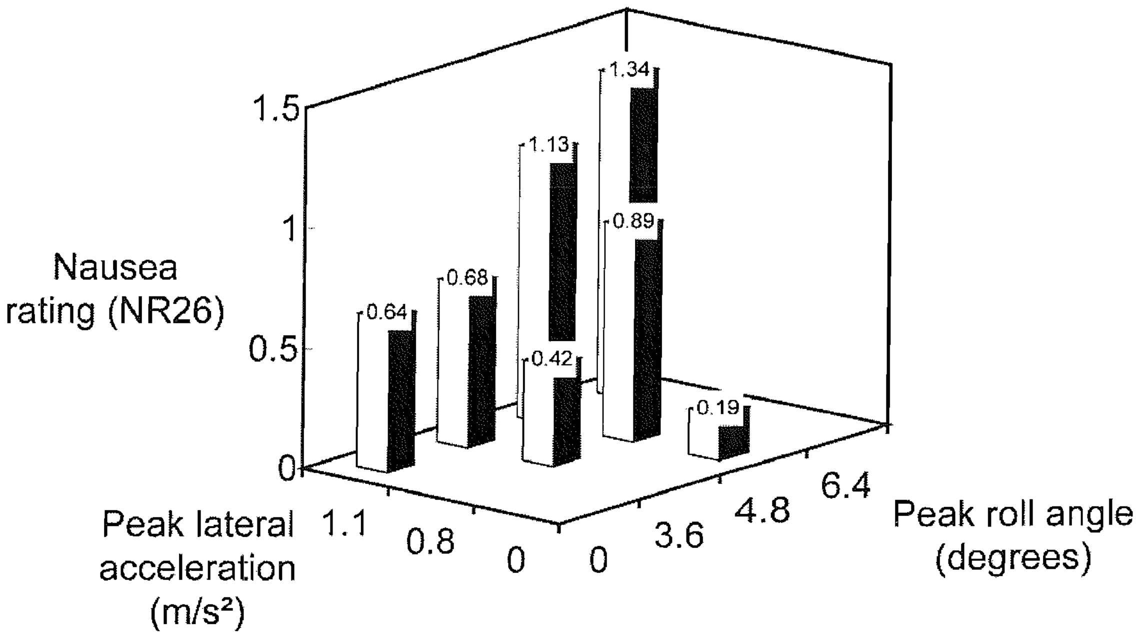


Figure 2.37 Estimated marginal mean nausea ratings at the 26th minute of exposure for various combinations of lateral and roll oscillation with synthesised tilting-train motion waveforms (redrawn using data from Förstberg, 1999).

When undergoing curvilinear motion associated with lateral motion on a two-pole swing, subjects are exposed to lateral and vertical translation, and roll rotation. Stott *et al.* compared motion sickness reported by 12 susceptible subjects exposed to swing oscillations to that reported by the same subjects exposed to each of the component lateral, vertical and rotational motions (Stott *et al.*, 2000). The swing oscillated at 0.285 Hz through an angle of ±30° and the peak acceleration at the subject head height was 4.37 m/s^2. The peak vertical acceleration at the subjects head on the swing was 1.8 m/s^2 but at twice the swing stimulus frequency, 0.57 Hz. Swing motion was found to be more nauseogenic that the equivalent horizontal oscillatory motion. Both swing motion and horizontal acceleration were more nauseogenic than vertical or roll oscillation.

2.10.8 Studies of translation with actively and passively induced rotation

Two experiments were devised to test whether passive or active changes in orientation with respect to an oscillating gravito-inertial force vector would influence motion sickness (Golding *et al.*, 2003). Gravito-inertial force oscillations were generated by Earth-horizontal fore-and-aft translation. Changes in orientation were facilitated by pitch motions, generated either by whole-body movements arising from an active suspension system or by active head movements initiated by the subject. With passive and active pitch movements, two conditions were used to investigate motion sickness when the subjects' head-vertical (*z*) axis was aligned (in phase) or misaligned (180° out of phase) with the gravito-inertial force. With active head pitch movements, subjects underwent 0.2 Hz fore-and-aft oscillation with ± 3.1 m/s^2 peak acceleration, whilst subjects underwent 0.176 Hz fore-and-aft oscillation with ± 2.0 m/s^2 peak acceleration with the passive pitch movements. Twelve different subjects were used in each experiment. Active head movements aligned to the gravito-inertial force caused significantly longer times to motion end-point than misaligned active head movements; however the converse was true with passive whole body motions. The authors concluded that whether or not compensatory tilting protects against or contributes to motion sickness may be influenced by whether tilting is under the active control of the person or under external control.

2.10.9 Effect of motion waveform

Only one study has explicitly studied the effect on motion sickness of the motion waveform: Guignard and McCauley (Guignard and McCauley, 1982) exposed independent groups of 31 or more subjects to vertical oscillation with complex periodic waveforms. Reports of motion sickness were investigated in five conditions, including a control condition involving sinusoidal vertical oscillation with a fundamental frequency of 0.17 Hz. Subjects exposed to the four complex motion waveforms experienced oscillation at the fundamental frequency combined with oscillation at either the second or third harmonic frequency. The relative phases and acceleration magnitudes of the fundamental and harmonic frequencies were varied. The root-mean-square acceleration was not held constant across conditions and ranged from 0.14 to 0.31G (1.4 to 3.1 ms^{-2}). In three out of the four complex motion conditions the recorded motion sickness incidence was not significantly different to the motion sickness obtained with just the fundamental motion. The only significant difference was found when the magnitude of the fundamental frequency was significantly lower than that of the harmonic (2^{nd}). The authors suggested that no simple additive model (e.g. using the r.m.s magnitude of the waveform components) could be used to predict motion sickness incidence. The authors did not rule out the possibility that the findings may have been due to chance.

2.10.10 Discussion and conclusions

Studies of horizontal and vertical translational oscillations found that motion sickness susceptibility tends to peak with oscillation at frequencies in the region 0.16 to 0.2 Hz, if using the same acceleration at all frequencies; although only two frequencies have been studied below this range. With horizontal and vertical motions, motion sickness tended to increase with increasing acceleration magnitude, although a linear relationship with motion sickness was only found with the vertical motion. The relative influence of vertical and horizontal oscillation is unclear but some studies have suggested that horizontal oscillation is more nauseogenic than vertical oscillation, but the effect may depend on the static orientation of the subject (e.g. whether seated or supine).

Rotational oscillations about horizontal axes, whether in pitch, roll, or with both combined, do not provoke significant motion sickness and are not as nauseogenic as horizontal or vertical translational oscillations; however, with these motions, any observed motion sickness, however small, may be dependent on the rotation angle.

Compared to when absent, the incidence of motion sickness does not appear to be significantly different when pitch and/or roll oscillations are added to large amplitude (displacement) vertical oscillation (e.g. Morton *et al.*, 1947 and McCauley *et al.* 1976). Conversely, the influence of additional roll and pitch may be significant with small amplitudes of vertical oscillation (Wertheim *et al.*, 1998). Motion sickness increased monotonically with either increasing lateral or roll oscillation amplitude when coupled in phase (Förstberg, 1999). Therefore, the interaction between translation and rotation appears "non-linear", although the true nature of the interaction and the effect of frequency are unknown. The effect also may depend on the relative phase of the motions and whether active or passive movements are employed (Golding *et al.* 2003).

2.11 DISCUSSION AND CONCLUSIONS

Motion sickness is a syndrome characterised by a collection of signs and symptoms. There is no gold standard for the assessment of motion sickness and for ethical and practical purposes the motion sickness syndrome is assessed using an illness rating scale.

In an Earth-bound environment, forces arise from inertial motion and from the Earth's gravitational field. A human's force environment is characterised by the magnitude and direction of the gravito-inertial force and the orientation of the subject's basicentric coordinate system relative to an inertial geocentric coordinate system. The relationships between the forces and accelerations in a subject referenced basicentric and those in an inertial geocentric coordinate system are more easily stated when considering movements in only two orthogonal directions.

Gravito-inertial forces and angular velocities are sensed by the otoliths and semicircular canals. Somatosensory information may indicate gravito-inertial forces and optic flow information from the eyes may be used to sense translational and angular movement; however the manner in which information from the various systems is integrated, and therefore the manner in which the integrated information affects motion sickness is not known.

Tilting-trains were developed to reduce the forces felt by passengers such that train speeds were able to increase and travel times were able to decrease: tilting-trains use roll motion to reduce, or compensate, the lateral forces felt by passengers during curves by aligning more closely the vertical axis of the coach environment with the gravito-inertial force. Thus, at low frequencies, lateral accelerations and roll displacements arising from curvaceous track provide the dominant motions in tilting-trains.

It has been repeatedly observed that tilting-trains cause more motion sickness than conventional trains and motion sickness tends to increase with increasing roll-compensation. It is not clear what aspects of the tilting-train motions are responsible for causing sickness but studies have variously attributed the provocative stimulus to the covariant factors of the lateral and roll acceleration measured in the coach. Fore-and-aft, pitch and yaw motions have not been considered as contributors to sickness on tilting-trains. A more complete analysis of the relationships and characteristics of lateral, vertical, and roll motion in tilting-trains and their influences on motion sickness is required, including detailed analysis of the typical range of motion frequencies and magnitudes experienced on tilting-trains.

With relatively simple motion environments, where motion in one axis dominates motion in other axes, such as with vertical motion in ships, motion sickness is approximately linearly dependent on the acceleration magnitude. Studies of exposure to complex motion environments, such as in aeroplanes, have revealed little information about the manner in which combined-axes motion influences sickness. Fore-and-aft and lateral accelerations cause motion sickness in cars and coaches, although their influence is moderated to some extent by the visual scene and posture afforded to passengers.

Models of motion sickness have been developed around the concept of sensory conflict, where sensory conflict has been defined as a difference between some quantity derived from the sensed motion and another quantity expressing some expectation related to the sensation of motion. The sensory conflict models have tended to differ in their definitions of motion sensation and the associated expectation; however, a consistent factor in several recent models (Mayne's gravito-inertial force resolution model, Stott's postulates, the otolith tilt-translation reinterpretation hypothesis and the subjective vertical model) has been that conflicts arise from perceptual processing of the gravito-inertial force: processing, required to resolve the inherent ambiguity associated with the equivalence of gravity and inertial forces, causes sensory rearrangement/conflict.

Of the existing motion sickness models, only two sensory conflict models appear to be able to generate quantitative predictions: the subjective vertical model claims to be applicable to motions in more than one axis, although a multi-directional model has yet to be explicitly defined. Stott's postulates do not claim to predict quantitatively motion sickness, yet the components necessary to form a quantitative model may be present – the expected sensations arising from any measured motions were defined, such that, for these motions, it might be possible to calculate the degree of conflict and hence motion sickness.

With a seated upright posture and vertical acceleration, the resultant gravito-inertial force does not rotate relative to either the Earth or subject. In these conditions, the reviewed studies found motion sickness to be approximately linearly dependent on the acceleration magnitude; thus, motion sickness was also linearly dependent on the change in the gravito-inertial force magnitude. With a seated upright posture during Earth-horizontal oscillation, the orientation of the gravito-inertial force becomes inclined periodically relative to the Earth and a subject's vertical (z) axis (during fore-and-aft oscillation the gravito-inertial force is inclined from front to back and during lateral oscillation it is inclined from side to side). In the reviewed studies of motion sickness with horizontal oscillation, motion sickness was not linearly dependent on the horizontal acceleration magnitude. Unlike with vertical oscillation, with horizontal oscillation the magnitude of the resultant gravito-inertial force is not linearly related to the acceleration magnitude; however, it was not stated whether motion sickness increased linearly with increasing gravito-inertial force magnitude in the reviewed experiments. Susceptibility to motion sickness with horizontal oscillation may peak with oscillations in the frequency range 0.16 to 0.2 Hz; however there is very little data below 0.2 Hz to completely justify this conclusion.

In accordance with Stott's postulates, studies of rotation about a horizontal axis, which did not cause changes in the gravito-inertial force, failed to find significant motion sickness. Studies of combined translation and rotation suggest that the effect of their interaction on motion sickness is not linear; rotation by itself does not cause significant sickness but when added to translational motion, which otherwise by itself would not be considered particularly nauseogenic, the incidence of motion sickness can be significantly high. In the case of combined lateral and roll oscillation, when roll motion is added to reduce the lateral force felt by the subjects, significantly more sickness is reported than if there were only lateral oscillations. This trend is consistent with that observed in tilting-trains where increases in roll-compensation have caused increased reports of motion sickness.

In conclusion, it was decided that the objectives of the series of investigations conducted for this thesis should be:

i) to reduce the scope of the PhD to an investigation of motion sickness with motions in the plane formed by the lateral and vertical axes in an geocentric coordinate system;

ii) to identify the range of magnitudes and frequencies of lateral, vertical and roll motion to which passengers are exposed in tilting-trains;

iii) to conduct laboratory investigations of combined lateral and roll oscillations to identify the effects of frequency and relative magnitude between the component motions. The lateral motion will be roll-compensated by keeping the displacements of the two motions in phase such that when roll is added and its relative magnitude increased the lateral force felt by subjects will decrease;

iv) to study motion sickness with oscillations at frequencies below 0.2 Hz;

v) to identify the influence on motion sickness of the magnitude and direction of the gravito-inertial force in conditions of combined lateral and roll motion;

vi) to extrapolate Stott's postulates to a quantitative model of motion sickness to be tested against the findings of the experimental investigations;

vii) to compare the results from the laboratory studies within a broader context of the results from studies of motion sickness on tilting-trains.

CHAPTER 3 LOW-FREQUENCY MOTION IN TILTING-TRAINS

3.1 INTRODUCTION

Few publications have reported the characteristics of low-frequency oscillation in tilting-trains. Specifically, there have been few reported investigations designed to detail the range of frequencies, magnitudes and combinations of lateral and roll oscillation to which passengers are exposed during journeys on tilting-trains.

Previous studies of motion sickness in tilting-trains have tended to assess the force environment using the acceleration and forces measured in the passenger environment (e.g. using a basicentric coordinate system). In such cases, analysis of the causes of motion sickness becomes complex as the lateral and vertical forces and the roll oscillations are covariant and thus highly correlated. The influence on motion sickness of each variable then becomes difficult to infer.

In contrast, laboratory studies have tended to define motion exposures using geocentric coordinate systems, where translational and rotational accelerations and the orientation with respect to gravity can be varied independently. Thus, with independent variables in the laboratory, the relationships between motion and motion sickness can be determined more easily.

Using frequency domain analysis techniques, this chapter seeks to describe the magnitude and frequency ranges of the Earth-referenced lateral accelerations and roll displacements measured on-board an experimental tilting-TGV. The investigation also aims to determine the degree of roll compensation experienced by passengers. The analysis will help to identify a representative range of lateral and roll motions to be selected for study in the laboratory.

3.2 METHOD

3.2.1 Data

Field trials to test the performance of an experimental tilting TGV were undertaken in April 2000. Accelerometers and an angular rate sensor were used to measure the lateral and vertical accelerations (ms^{-2}) and the absolute roll velocity (°/s) in the centre of a passenger coach. Both the cant deficiency (mm), measured on the leading bogie of the passenger coach, and the train speed (km/h) were recorded continuously. The raw signals were digitised at a rate of 100 samples per second.

Data were selected from recordings taken during part of each journey on the main line between Paris and Toulouse (this line has been suggested as suitable for a tilting-train service). A section traversing a 120 km region of line located between Brives (500 km from Paris) and Caussade (620 km from Paris) was selected for analysis.

In total, seven journeys across this region were undertaken. These journeys were used to investigate the performance of the tilting-train with various combinations of cant deficiency and compensation: a first group of conditions investigated approximately constant tilt-compensation with varying cant deficiency; a second group investigated approximately constant cant deficiency but with varying tilt-compensation.

3.2.2 Signal conditioning and calculation of independent variables

All calculations, conditioning and analyses were performed using MATLAB (Version 6.0.0.88, Release 12; September 22nd, 2000; The MathWorks Inc.).

The absolute roll displacement of the tilting-train carriage relative to the Earth-horizontal, φ, cannot be measured directly and must be calculated from the measured absolute roll velocity by numerical integration. A trapezoidal integration function (cumtrapz.m) was used for this purpose. Prior to integration any offsets (non-zero mean) in the absolute roll velocity were removed by calculating the mean of the signal and removing it from each sample in the signal (using the detrend.m function). A 2-pole high-pass Butterworth filter with a cut-off frequency at 0.001 Hz also was applied to the roll velocity signal prior to integration.

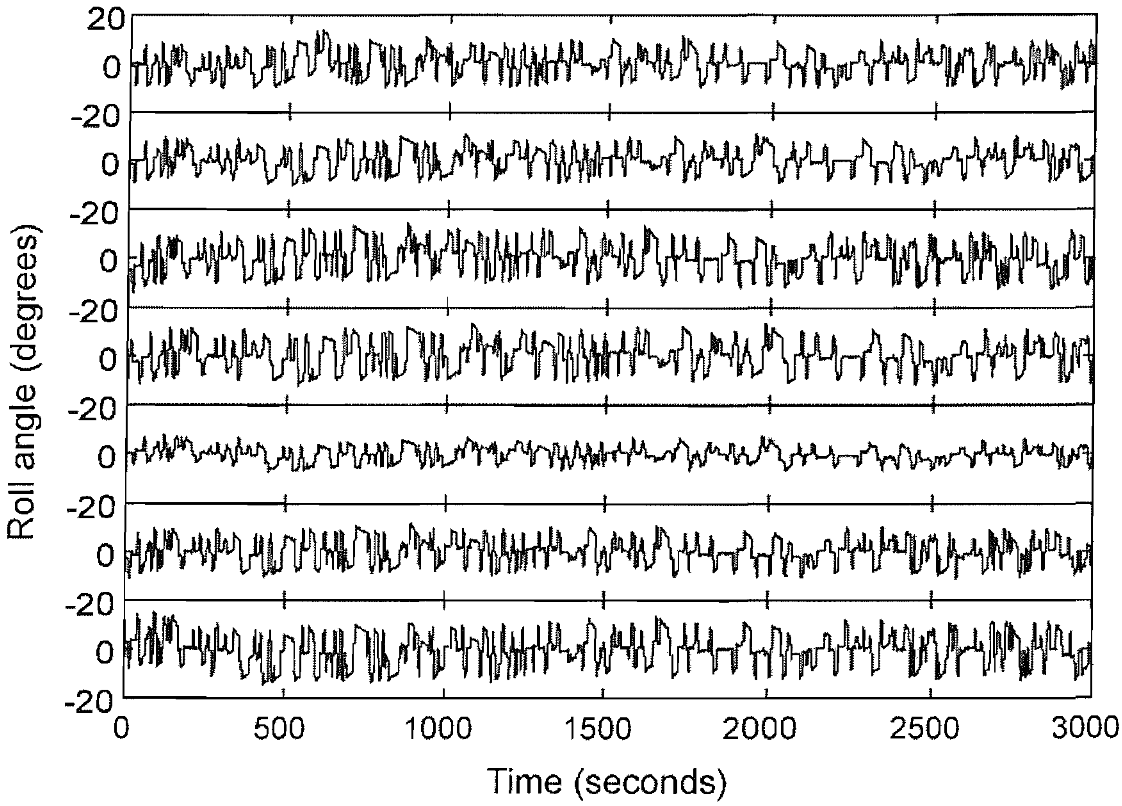


Figure 3.1 Extracted 50-minute segments of roll displacement signals calculated from integration of the roll velocities measured on an experimental tilting-TGV during seven journeys across a 120 km section of track between Brives and Caussade.

Any offset was removed from the roll displacement signal using the 'detrend.m' function. Figure 3.1 shows the roll displacement signals calculated for each test journey for the first 50 minutes of travel along the section between Brives and Caussade. No additional roll displacement data exists to help determine or quantify the absolute accuracy of these derived signals; however they appear to remain stable within the section of interest.

The Earth-lateral acceleration was calculated using the following approximation:

$$a_y = a'_y + g \cdot \varphi$$

where a_y and a_y' are the Earth-lateral accelerations and cabin lateral accelerations; g is the equivalent acceleration due to gravity (9.81 ms^{-2}) and φ is the absolute roll displacement of the coach floor relative to the Earth-horizontal (radians).

All subsequent analyses were completed after the signals of interest were low-pass filtered using an 8th order Type I Chebyshev filter with a cut-off frequency at 4 Hz and then decimated from a 100 to a 10 sample/s sampling frequency; the signals of interest are listed as follows: lateral and vertical accelerations measured in the coach; absolute roll velocity; cant deficiency; train velocity; and the calculated roll displacement and calculated Earth-lateral acceleration.

3.2.3 Calculation of train motion variables

For each of the seven journeys, two train motion variables were calculated to characterise the journeys so as to allow comparisons with other studies: the maximum cant deficiency was determined across the region of interest by using the 'max.m' function to find the positive peak value; the average train speed was calculated using the 'mean.m' function, which took the mean of the speed signal (measured on board the train) across the track region of interest.

3.2.4 Frequency analysis

After applying a Hamming window with 50% overlap, power spectral densities were calculated using Welch's method (using the function pwelch.m). The resolution of the power spectral density estimates was approximately 0.0015 Hz.

To evaluate the overall low-frequency (< 1 Hz) tilting-train motion magnitudes, root-mean-square accelerations (Earth-lateral, coach-lateral and coach vertical), roll velocities and roll displacements, were calculated for each journey. The root-mean-square values were calculated by finding the square-root of the summed area under the power spectral density curve across the frequency range 0 to 1 Hz:

$$RMS = \sqrt{\sum_{n=1}^{N_{1Hz}} \left(P_{xx,n} \times df\right)}$$

where *RMS* is the root-mean-square value; n is the index of power spectral density points; $P_{xx,n}$ is the magnitude of the *n*th power spectral density point; *df* is the frequency width (or resolution) between points; and $N_{1\ Hz}$ is the number of the power spectral density point corresponding to a frequency of 1 Hz.

Seven octave band root-mean-square values, with centre frequencies in the range 0.0125 to 1 Hz (0.016, 0.0315, 0.063, 0.125, 0.25, 0.5, and 1.0 Hz), were calculated for each signal. For each octave band centre frequency, *f*, the root-mean-square value, RMS_f, was calculated by taking the square-root of the summed area under the power spectral density curve within the frequency range specified by the lower and upper octave band limits; given by $f / \sqrt{2}$ and $f \times \sqrt{2}$ respectively:

$$RMS_f = \sqrt{\sum_{n=N_{f/\sqrt{2}}}^{N_{f\times\sqrt{2}}} \left(P_{xx,n} \times df\right)}$$

where n is the index of power spectral density points; $P_{xx,n}$ is the magnitude of the *n*th power spectral density point; *df* is the frequency width between points (or resolution); $N_{f/\sqrt{2}}$ is the number of the power spectral density point corresponding to the lower frequency of the octave band frequency range ($f / \sqrt{2}$); and $N_{f\times\sqrt{2}}$ is the number of the power spectral density point corresponding to the upper frequency of the octave band frequency range ($f \times \sqrt{2}$).

As a function of frequency, the degree of tilt compensation was quantified by calculating the compensation ratio for each octave band centre frequency, denoted c_f. The ratios were calculated by subtracting from unity the ratio of the coach-lateral and Earth-lateral octave band root-mean-square accelerations, denoted $a'_{y,f,rms}$ and $a_{y,f,rms}$ respectively:

$$c_f = 1 - \frac{a'_{y,f,rms}}{a_{y,f,rms}}$$

By assuming that the behaviour of the tilt system was constant across a range of frequencies above 0 Hz (a 'quasi-static approximation'; see Förstberg, 2000), the overall tilt performance of the tilting train was calculated. The frequency range over which the assumption was valid was determined from inspection of the compensation ratios at each octave band centre frequency. When calculated across the appropriate frequency range, the overall compensation, c, was found from the mean of the octave band compensation ratios:

$$c = \frac{\sum_{1}^{N} c_f}{N}$$

where N is the number of octave band centre frequencies across which the quasi-static approximation applies.

3.3 RESULTS

3.3.1 Summary of low frequency motion characteristics

The train journey conditions (speed, distance and cant deficiency) and overall low frequency motion characteristics, represented by the root-mean-square values for frequencies below 1 Hz, are given in Table 3.1 for each of the seven journeys and for each motion variable.

The train journeys occurred with average speeds ranging from 105 to 132 km/h and maximum cant deficiencies ranging from 158 to 317 mm. With these journeys the measured coach-referenced motions varied as follows: root-mean-square lateral accelerations ranged from 0.16 to 0.76 m/s²; root-mean-square vertical accelerations ranged from 0.11 to 0.20 m/s²; and root-mean-square roll velocities ranged from 0.68 to 1.77 °/s. When calculated from the integrated roll velocities, the root-mean-square roll displacements ranged from 3.14° to 6.43°. When derived from the coach-referenced lateral accelerations and the associated roll displacements, the root-mean-square Earth-lateral accelerations ranged from 1.14 to 1.74 m/s².

Table 3.1 Summary of the recorded motion conditions tested during 7 journeys on an experimental tilting TGV running over a 120 km section on the Paris – Toulouse line during April 2000. Quoted root-mean-square values are calculated to include frequencies only up to 1 Hz.

Journey (dd/mm)	Duration	Speed (mean) (km/h)	Cant deficiency (maximum) (mm)	Compensation ratio (0.016 – 0.125 Hz)	$\dot{\varphi}$ (°/s r.m.s)	φ (° r.m.s)	a_y (Earth) (m/s² r.m.s)	a_y' (Coach) (m/s² r.m.s)	a_z' (Coach) (m/s² r.m.s)
15/03	66m03s	109	158	0.86	1.41	6.04	1.18	0.16	0.13
16/03	68m43s	105	160	0.42	0.68	3.14	1.14	0.67	0.11
21/03	58m20s	123	256	0.57	1.34	5.08	1.50	0.65	0.17
22/03	56m02s	128	288	0.67	1.77	6.43	1.62	0.54	0.20
23/03	55m53s	129	278	0.54	1.43	5.13	1.62	0.76	0.17
28/03	65m35s	110	163	0.70	1.14	3.89	1.18	0.36	0.11
29/03	54m21s	132	317	0.59	1.73	6.02	1.74	0.72	0.20

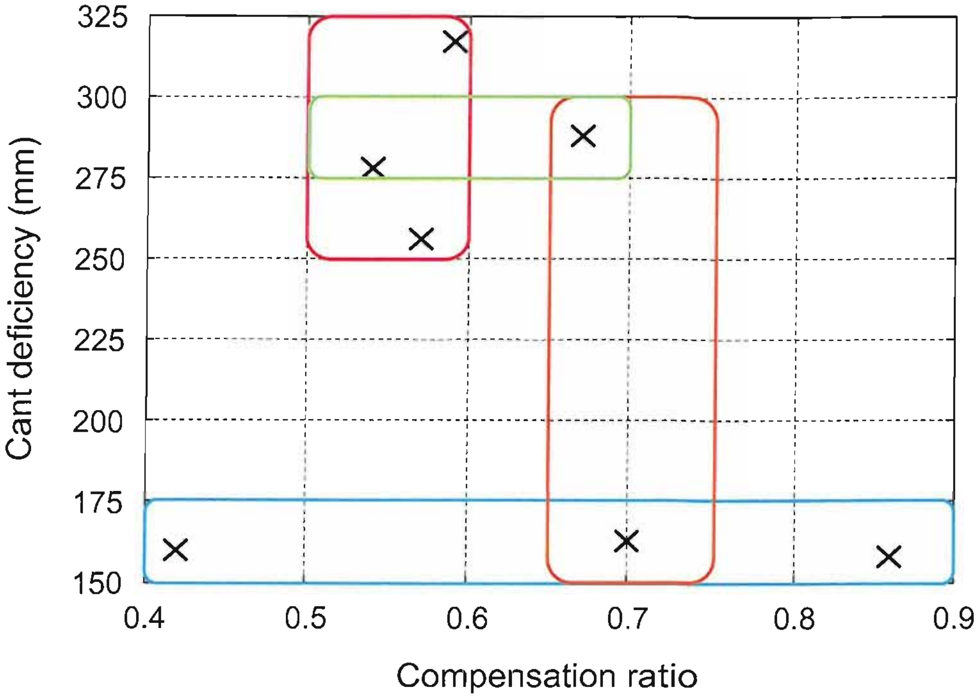


Figure 3.2 Selected grouping of conditions in to sets of either approximately constant cant deficiency and variable compensation or approximately constant compensation and variable cant deficiency.

3.3.2 Roll compensation

Inspection of the data suggested that the quasi-static assumption for roll compensation (i.e. that up to a given frequency the compensation was approximately constant) was valid for frequencies of lateral oscillation up to 0.125 Hz. Above this frequency, compensation ratios decreased with increasing frequency. Compensation ratios reported in this paper are therefore obtained from the mean compensation ratio across the octave band centre frequency in the range 0.016 to 0.125 Hz. The calculated overall compensation ratios ranged from 0.42 to 0.86.

3.3.3 Grouping of journeys

Four groups of journeys with either varying compensation and constant cant deficiency or varying cant deficiency and constant compensation were identified from the measurements. The four groups of journeys are illustrated in Figure 3.2 and are defined as follows: constant cant deficiency (in the approximate range 150 – 175 mm) and variable compensation ratio (in the approximate range 0.4 — 0.9); constant cant deficiency (in the approximate range 275 – 300 mm) and variable compensation ratio (in the approximate range 0.5 – 0.7); constant compensation ratio (in the approximate range 0.5 – 0.6) and variable cant deficiency (in the approximate range 250 – 325); and constant compensation ratio (in the approximate range 0.65 – 0.75) and variable cant deficiency (in the approximate range 150 – 300). The relationships between the motion variables will be illustrated by exploration of the four groups of journeys.

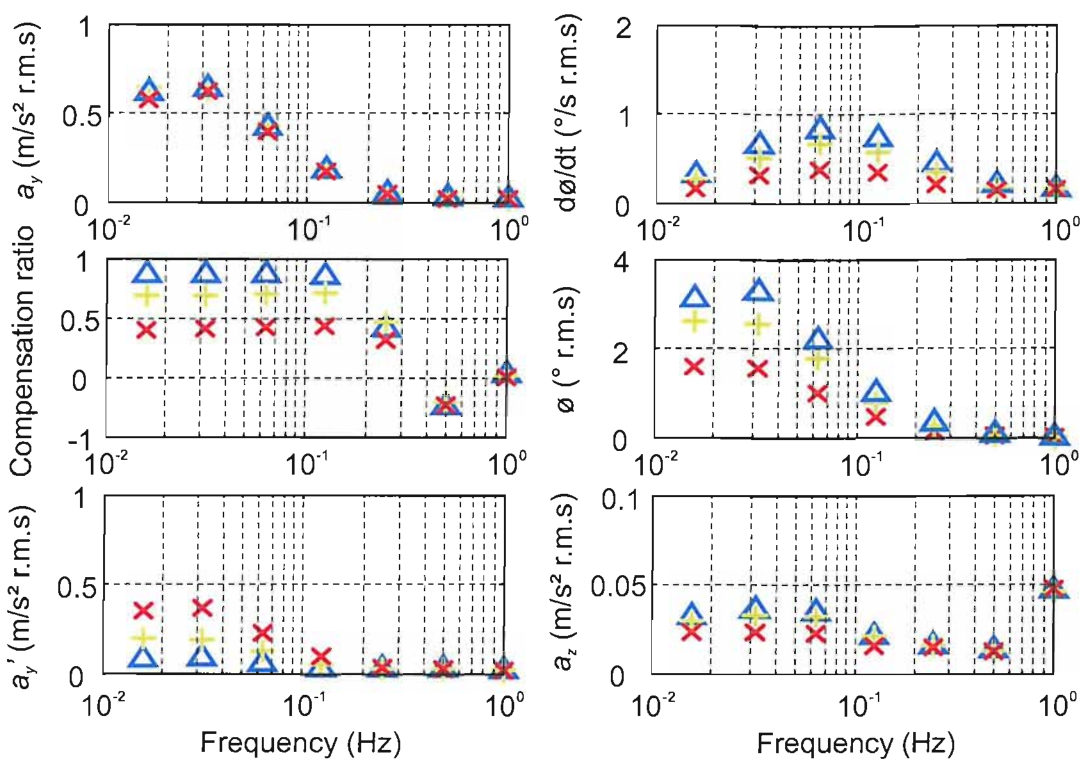


Figure 3.3 Earth-lateral acceleration, roll velocity and the resulting roll displacement, compensation ratio, subject lateral acceleration and subject vertical acceleration for three journeys with approximately constant cant deficiency (150 – 175 mm) but variable compensation ratio (0.4 – 0.9). Symbols indicate compensation ratio (cant deficiency): red cross: 0.42 (160 mm); green plus: 0.70 (163 mm); and blue triangle: 0.86 (158 mm).

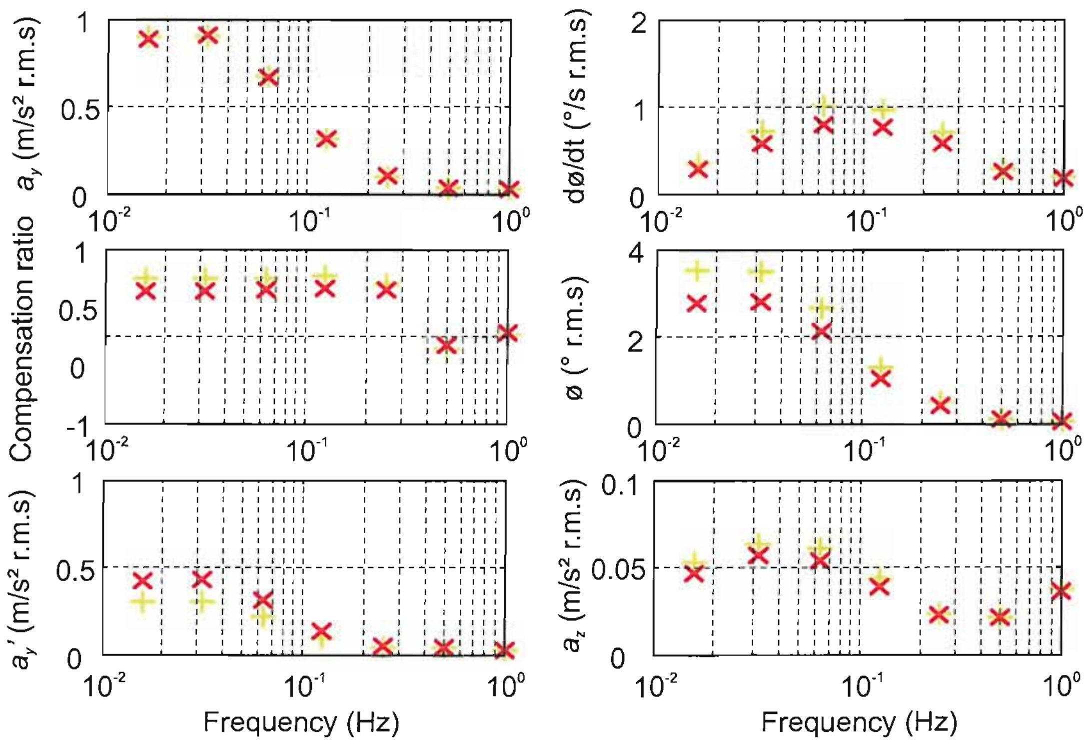


Figure 3.4 Earth-lateral acceleration, roll velocity and the resulting roll displacement, compensation ratio, subject lateral acceleration and subject vertical acceleration for three journeys with approximately constant cant deficiency (275 – 300 mm) but variable compensation ratio (0.5 – 0.7). Symbols indicate compensation ratio: red cross: 0.54 (278 mm); and green plus: 0.67 (288 mm).

3.3.4 Effect of compensation with approximately constant cant deficiency

For three journeys with approximately constant cant deficiency but variable compensation ratio, Figure 3.3 plots graphically octave-band root-mean-square values for the coach-referenced lateral and vertical accelerations, the Earth-lateral accelerations and the roll velocities and roll displacements. The compensation ratio at each octave-band centre frequency is also shown. Figure 3.4 depicts similar information but for two other journeys with constant cant deficiency but variable compensation ratio.

Train velocities ranged from 105 to 110 km/h for the group of journeys shown in Figure 3.3 and from 128 to 129 km/h for the group of journeys shown in Figure 3.4. With three journeys with maximum cant deficiencies in the range from 158 to 163 mm (as shown in Figure 3.3), the root-mean-square Earth-lateral accelerations at frequencies in the range up to 1 Hz ranged from 1.14 to 1.18 m/s². Similarly, with two journeys with maximum cant deficiencies in the range from 278 to 288 mm (as shown in Figure 3.4), the root-mean-square Earth-lateral accelerations at frequencies in the range up to 1 Hz were calculated as 1.62 m/s². Thus, Figure 3.3 and Figure 3.4 separately show group of journeys each with approximately constant mean speed, constant maximum cant deficiency and constant Earth-lateral acceleration: the top left panes of these Figures also suggest that, across the respective groups of journeys, the Earth-lateral accelerations were approximately constant.

The middle left panes in Figure 3.3 and Figure 3.4 suggest that, for each journey and for frequencies in the range from 0.016 to 0.125 Hz, the compensation was approximately constant. With approximately constant Earth-lateral acceleration and octave-band centre frequencies in the range from 0.016 to 0.125 Hz, Figure 3.3 and Figure 3.4 demonstrate decreasing subject-lateral acceleration and increasing roll displacement and subject-vertical acceleration with increasing compensation. The observations were confirmed by root-mean-square values for motion frequencies less than 1 Hz: with approximately constant Earth-lateral accelerations (ranging from 1.14 to 1.18 m/s²) and compensation ratios increasing in the range from 0.42 to 0.86 (Figure 3.3), root-mean-square subject-lateral accelerations decreased through the range from 0.67 to 0.16 m/s², root-mean-square subject-vertical accelerations increased in the range from 0.11 to 0.13 m/s², and root-mean-square roll displacements increased through the range from 3.14 to 6.04 degrees; likewise, with approximately constant Earth-lateral accelerations (1.62 m/s²) and compensation ratios increasing in the range from 0.54 to 0.67 (Figure 3.4), root-mean-square subject-lateral accelerations decreased through the range from 0.76 to 0.54 m/s², root-mean-square subject-vertical accelerations increased in the range from 0.17 to 0.20 m/s², and root-mean-square roll displacements increased through the range from 5.13 to 6.43 degrees.

The overall root-mean-square coach-vertical acceleration magnitudes were low; increases in compensation produced significant changes in magnitude.

With all conditions shown in Figures 3.3 and 3.4, the root-mean square roll velocities were highest with oscillations in the frequency range 0.063 to 0.125 Hz. There is also some indication that the octave-band root-mean-square values in all axes and all reference frames decreased with decreasing frequency below 0.0315 Hz.

3.3.5 Effect of cant deficiency with approximately constant compensation

For three journeys with constant compensation ratio and variable cant deficiency, Figure 3.5 presents octave band root-mean-square values for the coach-referenced lateral and vertical accelerations, the Earth-lateral accelerations and the roll velocities and roll displacements. The compensation ratio at each octave-band centre frequency is also shown. Figure 3.6 depicts similar information but for two other journeys with constant compensation ratio and variable cant deficiency.

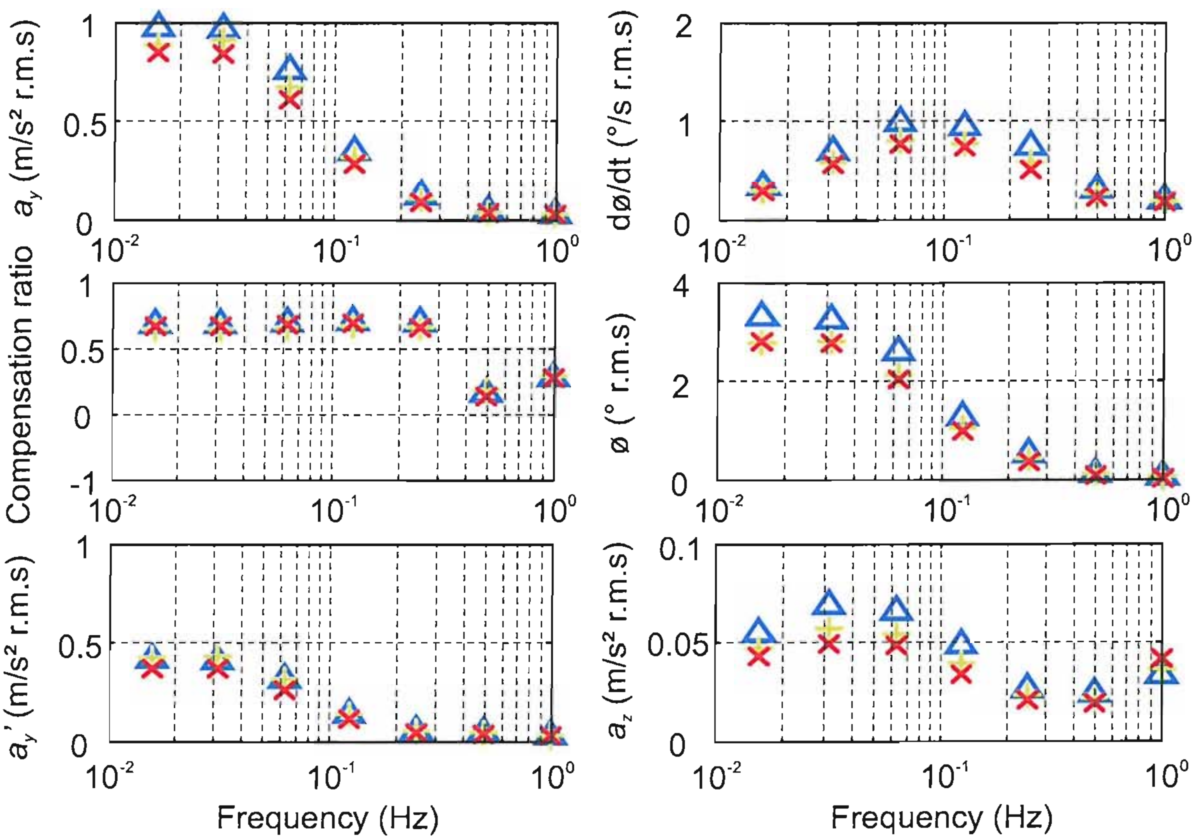


Figure 3.5 Earth-lateral acceleration, roll velocity and the resulting roll displacement, compensation ratio, subject lateral acceleration and subject vertical acceleration for three journeys with approximately constant compensation ratio (0.5 – 0.6) but variable cant deficiency (250 – 325 mm). Symbols indicate cant deficiency, in millimetres (compensation ratio): red cross: 256 (0.57); green plus: 278 (0.54); and blue triangle: 317 (0.59).

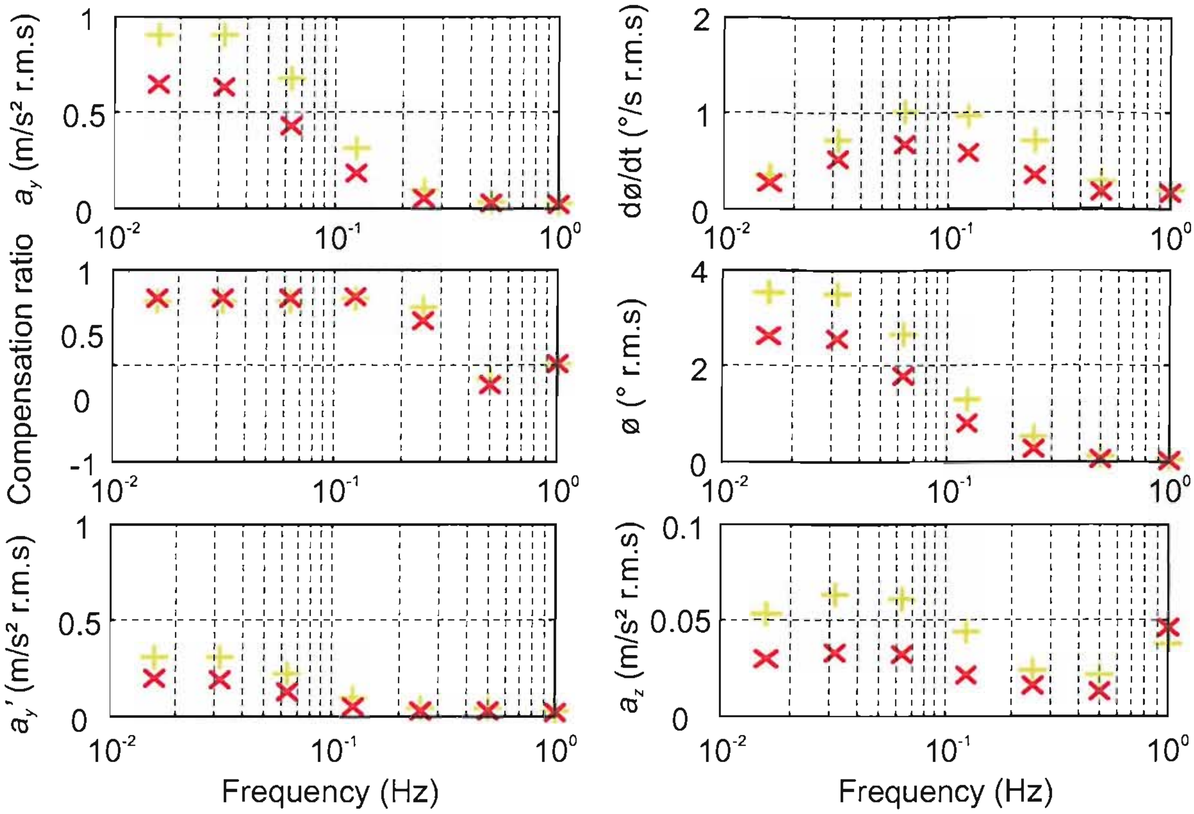


Figure 3.6 Earth-lateral acceleration, roll velocity and the resulting roll displacement, compensation ratio, subject lateral acceleration and subject vertical acceleration for three journeys with approximately constant compensation ratio (0.65 – 0.75) but variable cant deficiency (150 – 300 mm). Symbols indicate cant deficiency, in millimetres (compensation ratio): red cross: 163 (0.70); and green plus: 288 (0.67).

Mean train velocities ranged from 123 to 132 km/h for the group of journeys shown in Figure 3.5 and from 110 to 128 for the group of journeys shown in Figure 3.6; the respective maximum cant deficiencies for the two groups of journeys ranged from 256 to 317 mm and from 163 to 288 mm.

The middle left panes in Figure 3.5 and Figure 3.6 confirm that, across the journeys within each group and for frequencies in the range from 0.016 to 0.125 Hz, the compensation was approximately constant. With these groups of conditions, Figure 3.5 and Figure 3.6 demonstrate increasing subject-lateral acceleration, roll displacement and subject-vertical acceleration with increasing compensation. The observations were confirmed by root-mean-square values calculated for motion frequencies less than 1 Hz: with compensation ratios ranging from 0.54 to 0.59 and Earth-lateral accelerations increasing in the range from 1.50 to 1.74 m/s² (Figure 3.5), root-mean-square subject-lateral accelerations increased through the range from 0.65 to 0.70 m/s², root-mean-square subject-vertical accelerations increased in the range from 0.17 to 0.20 m/s², and root-mean-square roll displacements increased through the range from 5.08 to 6.02 degrees; likewise, with compensation ratios ranging from 0.67 to 0.70 and Earth-lateral accelerations increasing in the range from 1.18 to 1.62 m/s² (Figure 3.6), root-mean-square subject-lateral accelerations increased through the range from 0.36 to 0.54 m/s², root-mean-square subject-vertical accelerations increased in the range from 0.11 to 0.20 m/s², and root-mean-square roll displacements increased through the range from 3.89 to 6.43 degrees.

The overall root-mean-square coach-vertical acceleration magnitudes were low; increases in Earth-lateral acceleration produced the most significant changes in magnitude.

With all conditions shown in Figures 3.5 and 3.6, the root-mean square roll velocities were highest with oscillations in the frequency range 0.063 to 0.125 Hz. There is also some indication that the octave-band root-mean-square values in all axes and all reference frames decreased with decreasing frequency below 0.0315 Hz.

3.4 DISCUSSION

3.4.1 Low frequency tilting-train motion behaviour

Inspection of the various root-mean square motion variables indicated that the low-frequency tilting-train lateral and vertical accelerations and roll motions followed the relationships discussed in Section 2.5: with constant Earth-lateral acceleration the roll displacements and coach-vertical accelerations increased and the coach-lateral accelerations decreased with increasing roll-compensation. Similarly, with constant roll-compensation, the roll displacements and the coach-lateral and coach-vertical accelerations increased with increasing Earth-lateral acceleration.

Quasi-static assumptions have been used to describe the extent of roll-compensation achieved by tilting-trains: i.e. it has been assumed that roll-compensation is approximately constant at low-frequencies. For the case of an experimental tilting-TGV, the analysis presented here showed that this assumption can be considered correct.

3.4.2 Range of motions for laboratory investigations

In order to better understand the causes of motion sickness on tilting-trains, it was concluded that it was useful to define tilting-train motions in terms of independent motion variables, which are easily manipulated in the laboratory environment, rather than using the covariant coach-referenced variables. Thus, the aims of this investigation were to determine the range of Earth-lateral accelerations and roll displacements experienced during travel on a tilting-TGV and to determine the subsequent extent of the roll compensation.

Inspection of the octave-band root-mean-square values shows that for all axes of motion and reference frames, the magnitudes tended to peak at frequencies below 0.5 Hz. There was some indication that magnitudes decreased with decreasing frequency below 0.0315 Hz. It is suggested that, where possible, combinations of lateral and roll oscillation should be studied with frequencies in the range 0.0315 to 0.8 Hz. Note that although there appeared to be little roll-compensation at frequencies above 0.125 Hz, it is possible that other trains and journeys might produce significant Earth-lateral and roll motions in this frequency range.

The overall root-mean-square coach-vertical acceleration magnitudes were low, indicating that passengers could not have been exposed to Earth-vertical motion to any significant extent. Thus it is suggested that the experimental investigations will not need to include combinations of Earth-lateral, Earth-vertical and roll oscillation.

When considering oscillations below 1 Hz, the root-mean-square Earth-lateral accelerations were not greater than 1.74 m/s^2 and the roll displacements were not greater than 6.43°. Furthermore, at all frequencies in the range 0.016 to 1.0 Hz, the octave-band root-mean-square Earth-lateral accelerations remained below 1.0 m/s^2 and the octave-band root-mean-square roll displacements remained below 4°. Therefore, the motion magnitudes which will be studied in the laboratory will not need to exceed this range.

3.4.3 Application of findings and evaluation of methods

As suggested in Section 2.5.4, rail engineers tend to define the compensation ratio by considering the reduction in the lateral force felt by passengers relative to the lateral force in the plane of the track or bogie. However, the track already employs cant to compensate for the lateral forces. As the cant, and thus its resultant compensation, can change from location to location, the compensation as defined relative to the track cannot be considered an independent variable from which to predict motion sickness in tilting trains. This chapter aimed to determine the extent to which the roll compensation can be described relative to the Earth-horizontal, when derived from the measured roll velocity and coach-lateral acceleration. It is suggested that the analysis procedures used in this chapter might produce useful estimates of the degree of compensation relative to the Earth-horizontal such that it is easier to understand the true nature of the motions experienced in a tilting-train; however, future work will be required to determine the absolute accuracy of the analysis methods.

The findings also suggest that the extent of roll-compensation can be usefully expressed using quasi-static approximations, in this case with oscillations with frequencies up to 0.125 Hz.

3.5 CONCLUSIONS

Methods for calculating the Earth-referenced motions have been defined and the extent to which tilting-trains compensate for Earth-lateral accelerations has been determined. The magnitude and frequency ranges of the Earth-lateral, coach-lateral and coach-vertical accelerations and the roll displacements also have been defined.

CHAPTER 4 – APPARATUS AND EXPERIMENTAL PROCEDURE

4.1 INTRODUCTION

The experimental methods, equipment and protocols used during the course of the investigations are described in the following sections: motion simulation; the motion environment; subject selection, the experimental protocol (including considerations relating to ethical procedures); motion sickness measurement; and data analysis and statistical procedures.

4.2 MOTION SIMULATION

4.2.1 General description

A simulator capable of combined lateral and roll motion was commissioned for the purposes of performing the experimental work.

The simulator had an aluminium chassis, borne by rigid axles and nylon wheels, mounted on straight and level tubular steel rails to allow only movement in the horizontal axis. A rotating platform ('roll-rig') was mounted on the chassis, which enabled simultaneous translation and rotation (i.e. combined lateral and roll motion or combined fore-and-aft and pitch motion, depending on the orientation of the subject).

Figure 4.1 shows a schematic diagram of the horizontal-axes simulator in the centre and peak displacement (± 6 m) positions. The roll-rig was driven independently of the horizontally moving carriage and could achieve any angle of roll, up to 10 degrees, at any position along the track. In the horizontal translational and rotational axes, the simulator was capable of peak velocities of 5 m/s and 11.5 °/s respectively. The peak translational and rotational accelerations of the device respectively were 2.0 m/s^2 and 60 °/s^2. Nomograms showing the peak displacements, velocities and accelerations as a function of oscillation frequency for translation and rotation are shown in Figure 4.2.

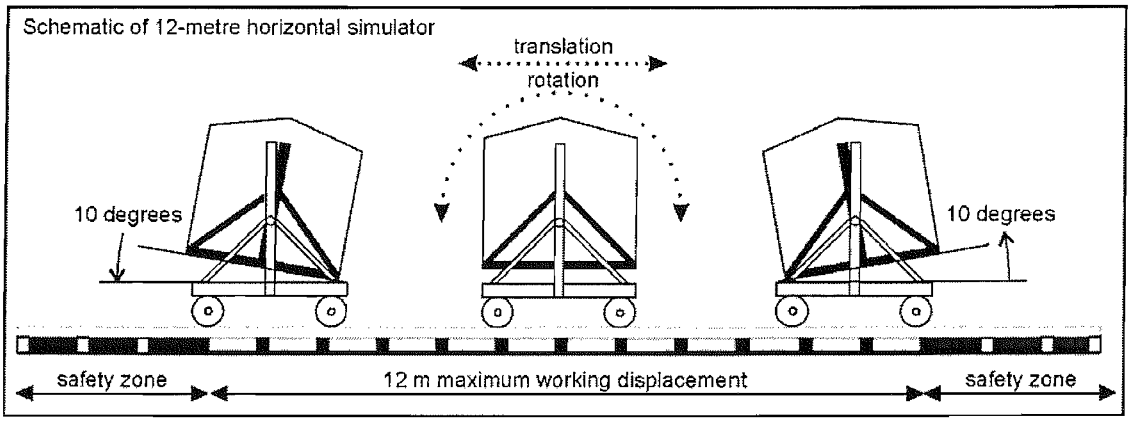
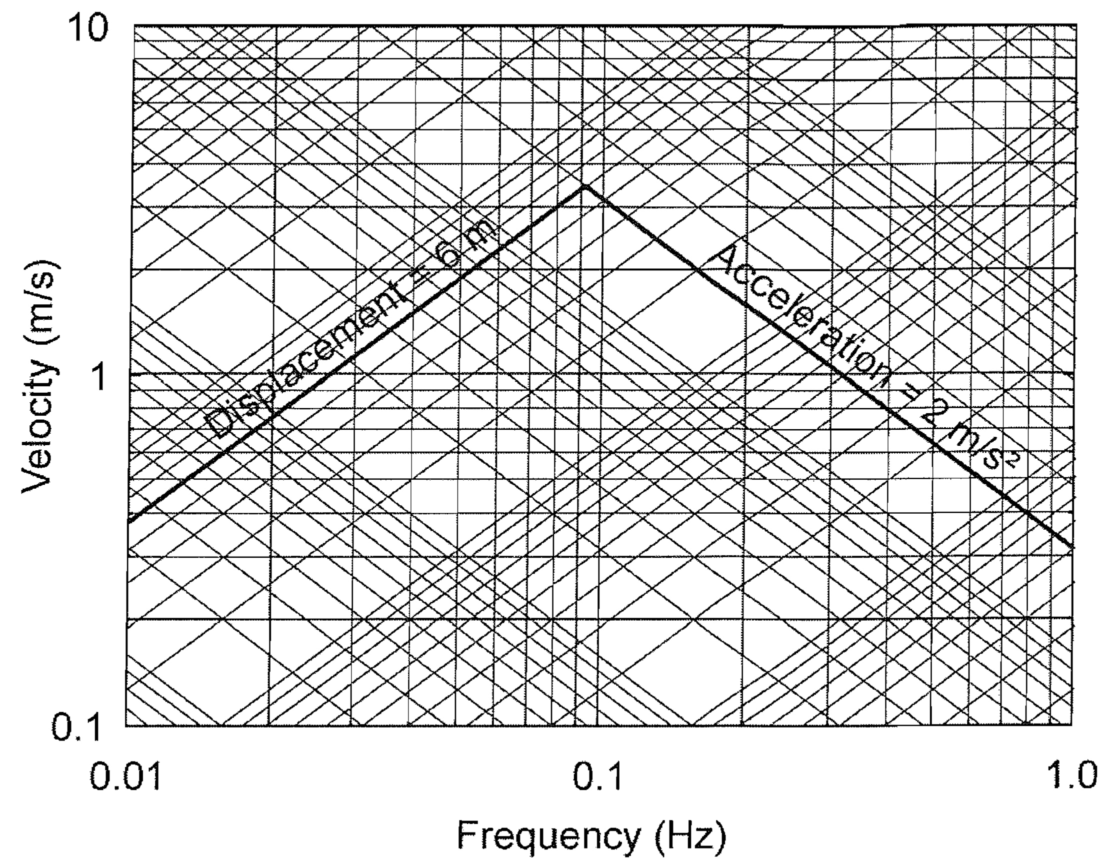


Figure 4.1 Schematic side view diagram of the 12-metre horizontal motion simulator.



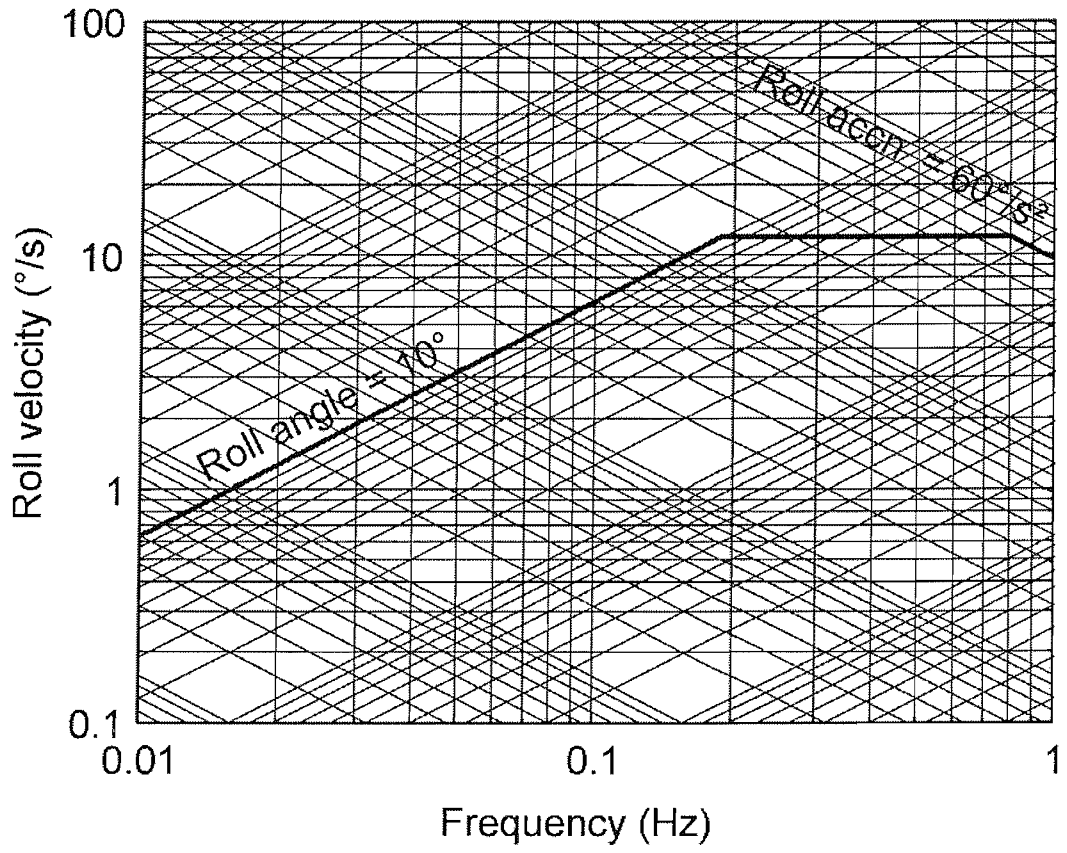


Figure 4.2 Nomograms showing the peak displacements, velocities and accelerations as a function of oscillation frequency for translation and rotation.

Power for horizontal motion was provided by a motor mounted internally within the simulator chassis. The motor drove against a fixed toothed-belt (fixed at each end of the 18 m track with an internal tension of approximately 3 kN) via gearing and a pinion. The belt was stiff to prevent undesirable movement from stretching (approximate belt displacement = 0.002 m given the approximate mass of carriage = 1250 kg, acceleration of carriage = 1.0 ms^{-2}, and belt stiffness = 620 kN/m). The toothed belt provided accurate position control by ensuring that there was minimal mechanical 'drift' or slipping of the carriage from the desired displacement.

The roll-rig consisted of a main frame supporting an internal motor and two parallel vertical posts at the mid-point of the length of the carriage. The vertical posts provided pivots around which a sub-frame supporting the roll platform rotated (see Figure 4.1). The arrangement was designed to allow the platform to be pivoted around varying centres of roll. Fixed below the platform on either side were two toothed-belts (fixed at each end of the roll platform) that were driven by pinions connected to the motor via a worm drive.

The motor driving the carriage was an AC asynchronous induction motor with a root-mean-square rating of 15 kW. The motor had a maximum speed of 1460 rpm and was controlled by an AC vector drive inverter (Eurotherm 620 Series). An AC asynchronous induction motor root-mean-square rated at 1.5 kW drove the roll-rig. The roll-rig motor had a maximum speed of 700 rpm and was also controlled by an AC vector drive inverter (Eurotherm 620 Series).

A cabin designed for the simulator fitted both the platform on top of the carriage and the platform provided on the roll device. It was constructed from 6 mm birch ply attached to a lightweight wood frame.

4.2.2 Inverter motor control and input signals

Displacement feedback control of the simulator was achieved with a loop from quadrature encoders (optical) attached to the horizontal and roll motor shafts. A proportional-integral (PI) control algorithm was used to adjust the inverter output to the motor accordingly. The PI parameters, proportional gain (P) and integration time (I) were set as shown in Table 4.1. The inverter units included a vector drive feature to improve efficiency.

Table 4.1 Proportional-Integral control algorithm parameters for the horizontal and rotational motion inverters.

	Proportional gain (P)	Integration time (I)
Horizontal motor inverter	21	50 ms
Rotational motor inverter	10	100 ms

Both the horizontal carriage and roll-rig inverters had an input range of ±10 volts, which after gearing corresponded to pinion speeds of ±5 ms^{-1} and ±0.245 ms^{-1} respectively. The horizontal motion scaling-factor between the inverter input and the horizontal carriage velocity output was 0.5 ms^{-1}/volt. The scaling factor for the rotational motion was more complex: the resultant displacement of the roll platform was dependent on the height of the centre of roll and the geometry of the roll device. Thus, the scaling between the roll angle and the belt displacement required a geometric transformation dependent upon the height of the centre of roll. The transformation is expressed in Appendix B with a diagram showing the dimensions and geometry of the simulator. After specifying the desired roll displacement, the resultant belt displacement had to be differentiated to find the required belt velocity.

4.2.3 Dynamic response

Horizontal transfer function

The modulus, phase and coherency of the frequency response function of the horizontal motion system were calculated from a desired acceleration signal and an acceleration signal measured on the simulator chassis (Figure 4.3). The digital input signal was a Gaussian random signal of 750 s duration, sampled at 50.0 samples per second and high-pass and low-pass filtered at 0.05 and 1.0 Hz using 8-pole filters with Bessel characteristics. The transfer function estimate was calculated assuming an ideal linear system with extraneous noise on the output (i.e. it was calculated from the quotient of the cross-spectral density, between the desired input acceleration and the measured output acceleration, and the power spectrum of the desired input acceleration). After applying a Hanning window with zero overlap, cross- and power spectral densities were calculated using Welch's averaged periodogram method. The length of each fast Fourier transform estimate was 4096 samples and the frequency domain resolution was 0.012 Hz.

Figure 4.3 presents plots of the modulus, phase and coherency as a function of frequency and shows that the horizontal simulator approximately has a unity magnitude response and a linear phase characteristic in the frequency range 0.02 Hz to 0.8 Hz: when calculated using the expression below, the horizontal system phase characteristic was estimated to be a pure delay, τ, of duration 0.53 s:

$$\tau = -\frac{\partial \phi}{\partial \omega}$$

where, ϕ is the phase and ω is the angular frequency (in radians). This delay was consistent with the known response time of the feedback control system due to a computational delay (approximately 500 ms).

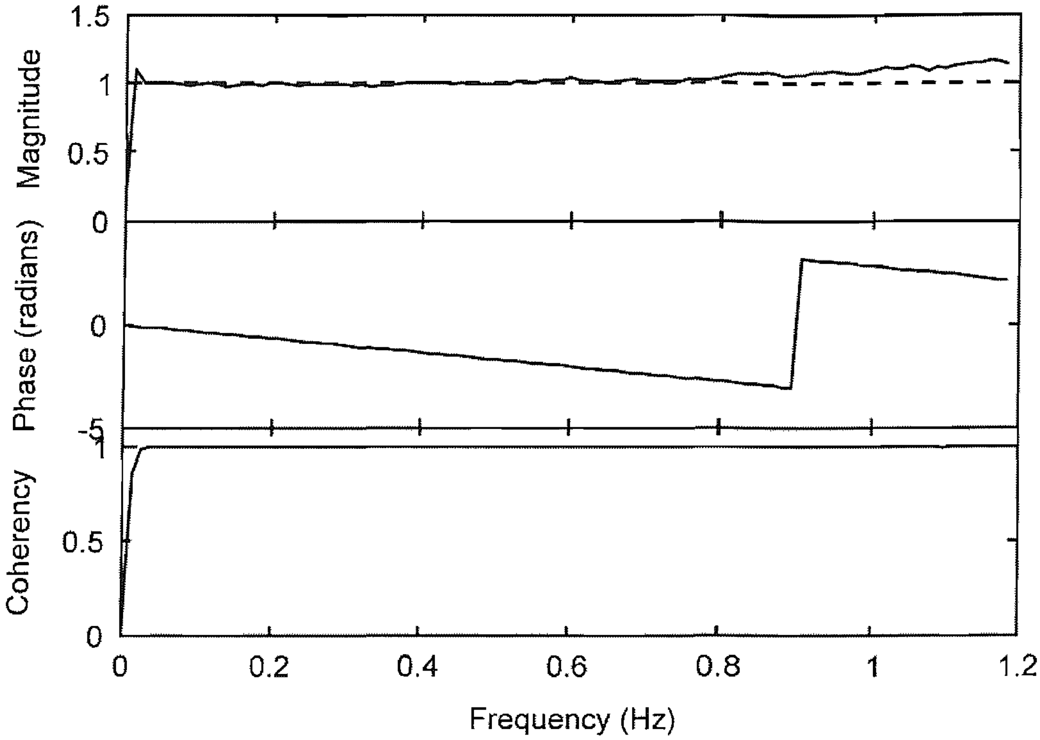


Figure 4.3 Frequency response function estimate of the 12-metre horizontal simulator, showing the modulus, phase and coherency.

Acceleration distortion

The acceleration distortion of the horizontal simulator was quantified for both translational and rotational sinusoidal oscillation with eight stimulus frequencies at 2/3 octave intervals across the range from 0.0315 to 0.8 Hz (0.0315, 0.05, 0.08, 0.125, 0.2, 0.315, 0.5 and 0.8 Hz). Each stimulus signal was created digitally using 50 samples per second and consisted of 20 complete cycles. With horizontal oscillation, the translational acceleration was measured on the simulator carriage. Of interest in these studies was the effect of using roll to compensate for the lateral force felt by subjects. Thus, the rotational distortion was assessed using the translational acceleration measured at the subject seat surface (located at the centre of roll), which changed with changing orientation with respect to gravity and therefore with changing roll angle. When evaluating the degree of distortion, it was assumed that only frequencies of oscillation up to 1 Hz were to be considered, as oscillation at frequencies above this range does not cause motion sickness. The expression used to quantify the acceleration distortion was given as follows

$$\text{Distortion }\% = \sqrt{\frac{\int_{\sqrt{2}\cdot f_0}^{1.0} P_{xx}\,df}{\int_{f_0/\sqrt{2}}^{\sqrt{2}\cdot f_0} P_{xx}\,df}} \times 100$$

where f_0 is the stimulus frequency and P_{xx} is the power spectral density of the acceleration signal: after applying a Hamming window with 50% overlap to the acceleration signal, the power spectral densities were calculated using Welch's average periodogram method. As the length of the acceleration signal varied with stimulus frequency (the number of cycles was constant across stimuli), the length of the Fourier transform estimates and the subsequent power-spectral-density resolutions varied: with the lowest stimulus frequency, 0.0315 Hz, the frequency resolution was approximately 0.006 Hz, and with the highest stimulus frequency, 0.8 Hz, the resolution was approximately 0.1 Hz.

The acceleration distortion mostly remained below 5% (Figure 4.4); it is suggested that the higher acceleration distortion (>10%) measured at 0.0315 Hz is likely due to the low power of the acceleration signal relative to the measurement noise and is not caused by real distortion.

4.2.4 Safety

The operator was prevented from direct contact with the moving simulator by a partitioning wall measuring about 2 metres in height. The top half of the partition was glass, allowing the operator a clear view of the simulator.

The simulator was equipped with a passive failure system, distinct from the main control system, designed to bring the simulator carriage safely to a stop in the event that displacement limits are exceeded. There were two braking systems: in the first instance a clutch brake was engaged and the power supply to the motor inverter removed if the carriage passed track switches set at the desired displacement limits.

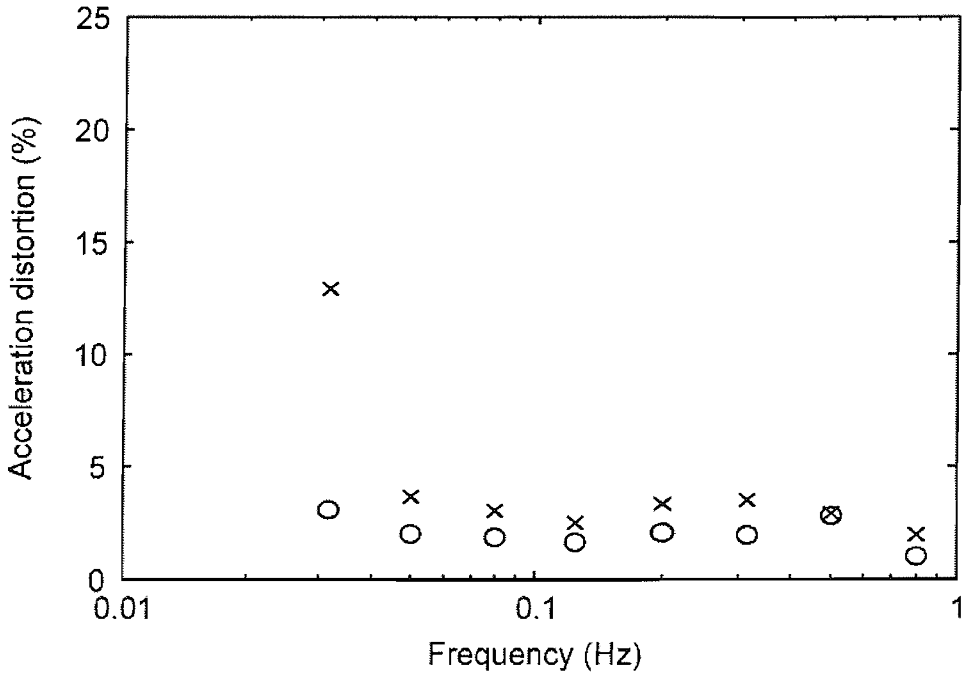


Figure 4.4 12-metre horizontal simulator acceleration distortion measured for translational and rotational motion. Cross = acceleration distortion with horizontal oscillation; Circle = translational acceleration distortion due to roll oscillation when measured at the centre of roll.

The secondary failure system consisted of 4 m long steel guides at each end of the track that were aligned with rubber pads (tank track pads) fixed to the underside of the carriage chassis. The rubber pads ran along the guides creating a friction force to retard the carriage. The guides provided braking force over three metres. The maximum available motor torque was insufficient to overcome the static friction force provided by this end-stop system. Hence, had the motor not been disengaged by the track switch system, the motor was be unable to drive the carriage through the end-stops. The failure system was passive and independent of human, or other active, controlling factors. In comparison with some alternatives, it had the advantage of being re-usable, causing little damage to either the guides or the carriage.

The operator and any subject using the simulator were provided with an emergency stop button. When pressed, the emergency stop button had the same effect as if the carriage had passed over a track displacement limit switch: it removed power to the inverter driving the motor and engaged the clutch brake.

According to ISO 13090-1 (International Organization for Standardization, 1998), in the event of a failure, a subject must not be exposed to a sustained or transient acceleration in excess of either a 1-second frequency-weighted running root-mean-square value of 10 ms^{-2}, or a fourth-power vibration dose value (VDV) of 17 $ms^{-1.75}$. Thus any retarding force imposed on a subject, planned or otherwise, must not be harmful to a subject.

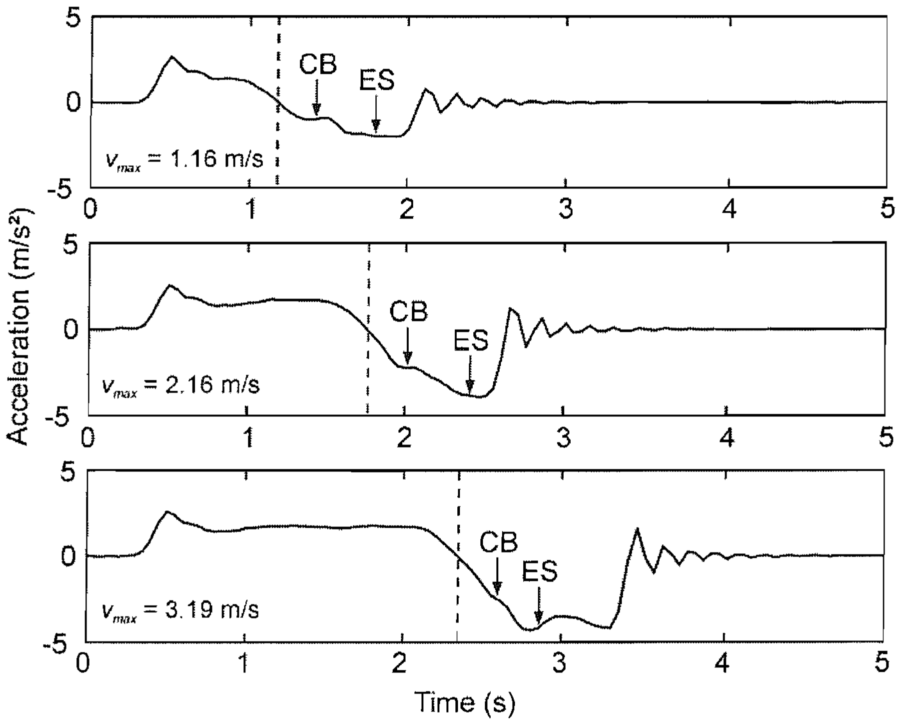


Figure 4.5 Acceleration profiles during emergency braking. The carriage accelerates from rest to a maximum velocity (v_{max}) at which time the disc brake (DB) is activated as the wheels pass over the displacement limit switch. The carriage then coasts into the end stops and decelerates (ES) to come back to rest.

Table 4.2 The vibration dose value (VDV) and maximum one-second running r.m.s acceleration for each of the three events shown in Figure 4.5. The values have been frequency weighted using Wd in accord with BS 6841 (1987).

Event number:	1	2	3
Starting velocity (m/s)	1.16	2.16	3.19
VDV ($m/s^{1.75}$)	1.13	2.09	2.33
Maximum running 1-second r.m.s (m/s^2)	0.61	1.13	1.7

The braking system performance was quantified by recording the acceleration during simulated events. Figure 4.5 shows acceleration profiles during emergency braking where the carriage passed the displacement limits that were specially positioned for the test, after accelerating to some speed (v_{max} m/s). The clutch brake was then activated (with deceleration marked by DB) and the carriage coasted almost immediately into the end-stops (with deceleration marked by ES). Table 4.2 shows vibration dose values calculated for three velocities of movement of the carriage past the displacement limits. The braking procedure resulted in vibration dose values significantly below those specified in ISO 13090-1.

4.3 MOTION MONITORING AND USER CONTROL

4.3.1 Motion signal specification

The desired input signals for horizontal and rotational inverters were created in MATLAB (Version 6.0.0.88, Release 12; September 22nd, 2000; The MathWorks Inc.). Appendix C shows the MATLAB program used to define the signals.

4.3.2 D/A and A/D conversion, signal conditioning and instrumentation

An *HVLab* data acquisition system (version 3.81) was used to supply motion command signals to the motor inverters and to measure the subsequent simulator accelerations. The *HVLab* system, under control of a personal computer (ACER, DX486) included a multifunction PC card (Advantech, PC Labs PCL-818) for D/A and A/D conversion. The stimulus and recorded acceleration signals were sampled at 30 samples per second during D/A and A/D conversion. The D/A output to the inverters were low-pass filtered at 1 Hz using analogue 0.1 – 10 kHz variable filters (KEMO VBF17, Kemo Ltd., Beckenham UK) with 48dB/octave roll-off characteristics. An accelerometer (Smiths Industries: ± 12g, 503 AD/32; S/N: AE 2653/77) was mounted on the simulator chassis to measure the Earth-horizontal acceleration produced by the simulator. A further accelerometer (Smiths Industries: ± 12g, 503 AD/32; S/N: AE 2983/77) was located at the level of the seat surface to measure the horizontal acceleration imposed on the subject at the subject-seat interface. After amplification (using HFRU-ISVR built accelerometer amplifiers) the measured acceleration signals were interfaced with the computer via a 16-channel break-out-box (Laplace Instruments) and were subsequently low-pass filtered at 5 Hz using an anti-aliasing filter PC card (Techfilter) prior to A/D conversion.

4.3.3 Experimenter motion monitoring and control

Visual contact with the simulator was maintained at all times by the experimenter (see Figure 4.6). A voltmeter (Thurlby 1504 true r.m.s voltmeter) and a roll displacement meter (HFRU designed and built with an analogue display) were used to monitor the horizontal and rotational motions respectively. The input signals were manually adjusted to remove any 'drifts' in the motion displacements: two signal amplifiers were required to convert the D/A output from 0 – 5 volt range to the ±10 volt range required for the horizontal and roll-rig motor inverters. The signal amplifier units included a potentiometer that allowed small adjustments to the signal offset (±120 mV).

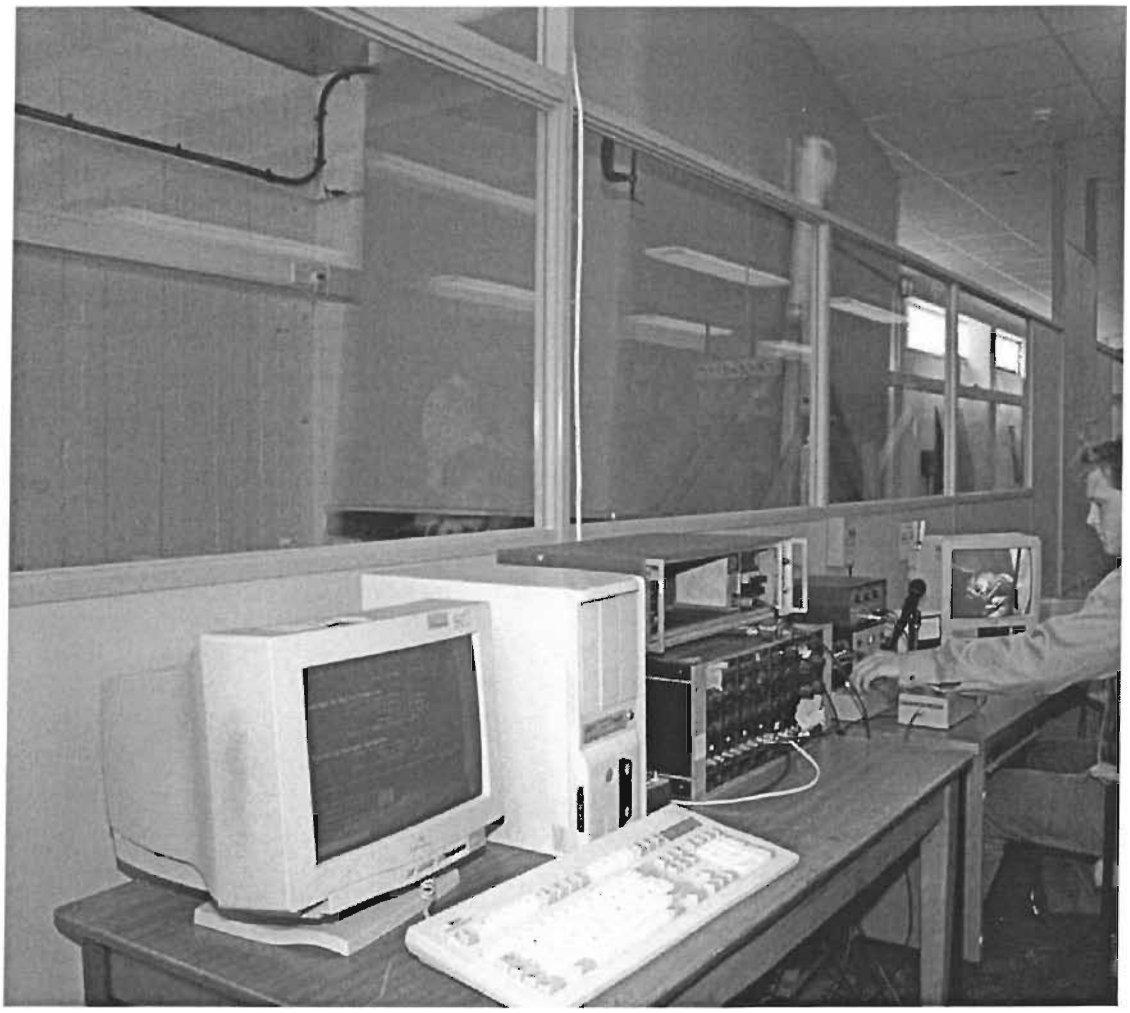


Figure 4.6 Control desk and simulator (undergoing combined lateral and roll motion). Visible on the desk are a computer based data acquisition system, signal conditioning apparatus, a microphone and a television to monitor subjects.

4.4 MOTION ENVIRONMENT

4.4.1 Cabin and seating

The experimental motion environment is shown in Figure 4.7. Subjects sat on a rigid chair within a rigid cabin (2000 mm x 1300 mm x 1900 mm) supported on the simulator platform. The cabin reduced external cues such as air movements, light and sound. The door to the cabin was rigid. The chair had a rigid flat supporting surface 400 mm above the platform of the simulator. The backrest on the chair was low, extending 245 mm above the seat surface (i.e., to the sitting elbow height for male adults aged 18 to 45 years): the subjects had to control the movements of their upper bodies due to a lack of support since this backrest maintained only the position of their buttocks. Subjects wore a loose lap belt for safety reasons. The subjects were instructed to sit with their feet 'square on the floor', their hands in their laps and to maintain a relaxed but upright posture whilst looking straight ahead at all times.

4.4.2 Vision

The cabin provided no external view. The subjects viewed a 0.4 by 0.3 metre reproduction of a fractal located directly in front of them on the internal wall of the cabin at a distance of 0.7 metres. The cabin was illuminated by a 40-watt filament bulb mounted in the roof of the cabin.

Figure 4.7 Internal view of the simulator with subject maintaining correct posture.

4.4.3 Auditory masking and communication

Subjects wore headphones (PRO-LUXE, PX-921) producing white noise (85 ± 1.5 dB(A), measured using a Knowles Electronics Manikin for Acoustic Research, KEMAR) to mask the sounds of the simulator. A random noise generator (Brüel and Kjær, type 1405) was used to supply the noise source via a headphone amplifier unit (HFRU built) and attenuator (Attenuator type 2120, Hatfield Instruments Ltd., Plymouth, England). The experimenter communicated with subjects via a microphone (Fico, UDM-326) by interrupting the white noise. The subjects were closed-circuit monitored by a video camera (Panasonic NV-A3B) connected to a television (Toshiba 14T01B). Throughout the experiment, the monitor allowed the experimenter to check the subjects' well-being, their posture and that their eyes were kept open.

4.4.4 Ventilation

A fan was fitted to the cabin, below and behind the chair, to provide a constant supply of air from the laboratory.

4.5 EXPERIMENTAL DESIGN

4.5.1 Introduction

Two alternative methods to the basic experimental design exist: i) a between-subject design (independent groups) involving two or more totally separate groups receiving different conditions of the independent variable and ii) a within-subject (repeated groups) design involving the same group of subjects receiving all the various conditions of the independent variable. The two methods differ in their approach to the control of subject variation (Davis, 1995).

4.5.2 Between-subject design, randomisation & matching

As by definition there are different subjects in each group, a between-subject design may lose statistical power because the groups may share different characteristics at the outset of the experiment which will influence their response. The influence of these differences can be minimised by using randomisation to give each subject an equal chance of being in each group, such that the differences are not eliminated but are randomly distributed between the groups (Davis, 1995). Although random allocation can not achieve the ideal of having an equal distribution between the groups it at least makes the probability of a skewed distribution very small: as the number of subjects in an experiment increases, so does the likelihood of attaining an equal distribution.

Randomisation of subjects to experimental groups will guard against certain error but will not increase the sensitivity (or power) of an experiment in detecting any effect of the independent variable (Davis, 1995). Sensitivity can be increased by matching subjects, such that any subject variable that is known to influence the independent variables, but is not controlled by the experimenter, is found equally in each group.

4.5.3 Within-subject design, order effects and carry-over effects

The problem of differences between subjects and the need for matching can be overcome by using the same subjects in each of the experimental conditions. In within-subject design experiments the subjects act as their own controls and when the subject performs differently under each condition then the effect of the independent variable is clear (Davis, 1995); however, two problems exist with within-subject design experiments and are related to the fact that the conditions in the experiment must be completed in series. The first is order effects, where repeated exposure influences the subject's performance regardless of the sequence of exposure to each condition. The second is carry-over effects where the response to one condition is dependent in some way on one or more of the conditions which preceded it. A latin-squares design may help to counterbalance a within-subject design experiment, such that each condition appears equally in each position; in which case any carry-over effects are not removed but are being controlled for by randomly distributing them across the exposures.

4.5.4 Selection of experimental design

A between-subject design was selected for the experimental work undertaken for this thesis on the basis that the problems associated with the differences between groups can be overcome by randomised allocation of subjects to conditions and by matching the subjects using a motion sickness susceptibility questionnaire (Section 4.6.3). The questionnaire was used to match the groups for various measures of a subject's susceptibility to motion sickness, as determined from their previous travel history: the measures of motion sickness susceptibility have been shown to be significant factors in the prediction of motion sickness (Mills and Griffin, 2000; Griffin and Mills 2002a; and Griffin and Mills 2002b). A within-subject design was dismissed as a possible experimental method as the effects of adaptation and habituation to different types of motion are not well known. Adaptation and habituation responses may cause order or carry-over effects, which make the experimental results difficult to interpret.

4.6 SUBJECT SELECTION

4.6.1 Subject sampling population

Subjects (aged 18 to 26 years) were sampled from the student and staff population of the University of Southampton.

4.6.2 Consent and screening

A health-screening questionnaire and consent form was completed by each subject prior to motion exposure (see Appendix D).

4.6.3 Motion sickness susceptibility questionnaire

A motion sickness susceptibility questionnaire was completed by each subject prior to motion exposure (Appendix E).

The subjects were allocated into groups of 20 subjects such that there were no significant differences between the groups in illness susceptibility in transport in the last year ($I_{susc(yr)}$), vomiting susceptibility in transport in the last year ($V_{susc(yr)}$), total susceptibility to vomiting in transport (V_{total}), total susceptibility to motion sickness in transport (M_{total}), total susceptibility to motion sickness on land transport (M_{land}) and total susceptibility to motion sickness on non-land transport ($M_{non\text{-}land}$). $I_{susc(yr)}$ is the number of times illness has occurred in the previous year in any form of transport, taking into account both the number of times the subject has travelled in a form of transport and the number of forms of transport the subject has travelled in. The definition of $V_{susc(yr)}$ is similar except that it refers to the total number of times vomiting has occurred in the past year. V_{total} refers to the number of times a subject has ever vomited in transport. These indices have been defined elsewhere (Griffin and Howarth, 2000).

4.7 EXPERIMENTAL PROTOCOL

4.7.1 Safety and ethical considerations

The subjects had an emergency stop button available to them during the experiment and they were able to terminate the experiment at any time without giving a reason. All experiments were approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

4.7.2 Experimental procedure

An instruction sheet detailing the experimental procedure was given to the subjects prior to commencing the experiment (Appendix F). After subjects had confirmed that they understood the procedure, they were led to the simulator, seated appropriately, given a brief verbal description of the procedure. When the subjects indicated that they were happy to continue the simulator door was closed and the exposure began. Subjects were exposed to only one condition.

Table 4.3 Illness rating scale

Rating	Corresponding symptoms
0	No symptoms
1	Any symptoms, however slight
2	Mild symptoms, e.g. stomach awareness, but not nausea
3	Mild nausea
4	Mild to moderate nausea
5	Moderate nausea but can continue
6	Moderate nausea and want to stop

4.8 MOTION SICKNESS MEASUREMENT

4.8.1 Subjective illness rating scale

At one-minute intervals during motion exposure, the subjects verbally rated their illness using a scale from 0 to 6, as shown in Table 4.3. The exposure was terminated when an illness rating of 6 was reached or the full 30-minute exposure had been completed. Average illness ratings (average of all the illness ratings reported by a subject over the 30-minute exposure) were calculated for each subject. Mean illness ratings at each minute of exposure and the proportion reporting each symptom over the whole exposure were calculated for each group of 20 subjects.

4.8.2 Symptom checklist

Subjects completed a symptom checklist (Appendix G) in order to indicate any symptoms they had experienced during the exposure. Symptoms included were: yawning, cold sweating, nausea, stomach awareness, dry mouth, increased salivation, headache, bodily warmth, dizziness, and drowsiness. The numbers of symptoms felt were accumulated to give a total symptom score for each subject.

4.9 DATA ANALYIS AND STATISTICAL PROCEDURES

4.9.1 Analysis tools

The motion data were analysed using *HVLab* software (v 3.81) and MATLAB software (Version 6.0.0.88, Release 12; September 22nd, 2000; The MathWorks Inc.). The subject data (illness ratings, symptom checklist and motion sickness susceptibility questionnaires) were stored and manipulated in a spreadsheet software package (Microsoft Excel 2000) and exported to a statistical software package (SPSS; version 12.0, SPSS, Chicago, IL) for analysis.

4.9.2 Kruskal-Wallis test for several independent samples

The Kruskal-Wallis test for several independent samples is a nonparametric procedure used to compare two or more groups of cases on one variable.

4.9.3 Mann-Whitney test for 2 independent samples

The Mann-Whitney test is a nonparametric equivalent to the Student's *t*-test and is used to test whether two independent samples are from the same population.

4.9.4 Cox regression analysis

Cox regression is a method for modelling time-to-event data in the presence of censored cases (i.e. cases in which the event of interest has not occurred). Cox regression uses models formed from predictor variables (covariates) to test which variables significantly influence the probability of the event occurring.

In these studies Cox regression was used to estimate the influence that various independent motion and subject variables had on the probability of a subject reaching a specific illness rating. The 'risk' associated with each variable was given by the exponent of the regression coefficient for that variable (e^{β}): the exponent of the regression coefficient represented the change in risk associated with a unit increase in the value of that variable. For categorical variables the exponent of the regression coefficient gave the relative risk (i.e., the risk associated with a case falling in one category relative to some reference category).

CHAPTER 5 EFFECT OF MOTION WAVEFORM (PILOT STUDY)

5.1 INTRODUCTION

A review of literature revealed that few publications have studied in detail the relative effects of sinusoidal oscillation and other motion waveforms on motion sickness. However, one study of vertical oscillation with complex motion waveforms suggested that (Guignard and McCauley, 1982) no simple additive model (e.g. using the r.m.s magnitude of the waveform components) could be used to predict motion sickness incidence, although the authors did not rule out the possibility that the findings may have been due to chance. There have been no investigations of the effect of motion waveform on motion sickness with lateral motion.

The aims of this pilot study are three-fold; i) to compare directly the effects on motion sickness of sinusoidal and broadband motion waveforms; ii) to estimate the extent to which a frequency weighting developed using sinusoidal lateral oscillation can be applied to broad-band random lateral motion waveforms; iii) examine the level of and variance in motion sickness amongst the exposed population so as to estimate the statistical power of the study and the number of subjects to be studied in future conditions.

In this investigation, the results from an earlier series of studies (Griffin and Mills, 2002a and 2002b) were used to compare the effects of motion waveform on motion sickness; the authors investigated motion sickness reported by 12 subjects exposed to sinusoidal oscillation at 0.2 Hz and 24 subjects exposed to a stationary condition. The experimental conditions in the earlier studies were identical to those used here. The stationary condition involved subjects sitting in an enclosed cabin but with no motion. Subjects were not informed that the cabin was stationary.

5.2 MOTION CONDITIONS

Subjects were exposed to an octave band Gaussian random motion with a centre frequency at 0.2 Hz. The limiting frequencies of the octave band were 0.14 and 0.28 Hz and the root-mean-square acceleration magnitude of the sinusoidal and random motions was 0.44 ms^{-2}. The desired random motion acceleration waveform was digitised at a rate of 20 samples per second and filtered using an octave band filter (as defined by BS 61260:1996; British Standards Institute, 1996) in MATLAB.

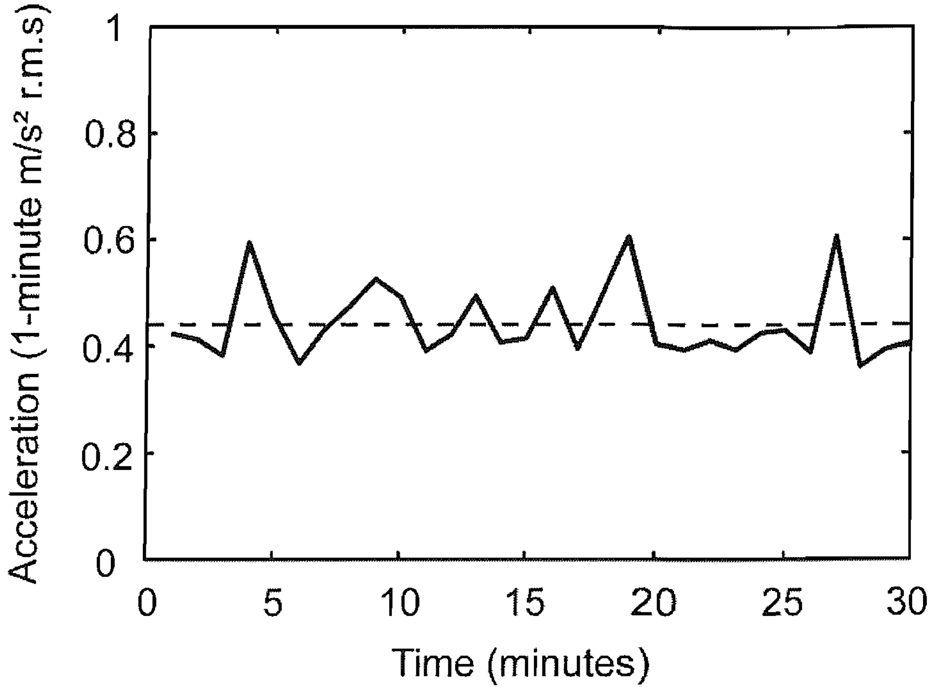


Figure 5.1 Variation of root-mean-square acceleration (for consecutive 1 minute periods) with respect to time.

The root-mean-square acceleration was calculated for consecutive one-minute segments of the signal, and was used to ensure that there were no obvious order effects inherent in the random signal. Figure 5.1 shows the variation of r.m.s magnitude of the acceleration signal with respect to time.

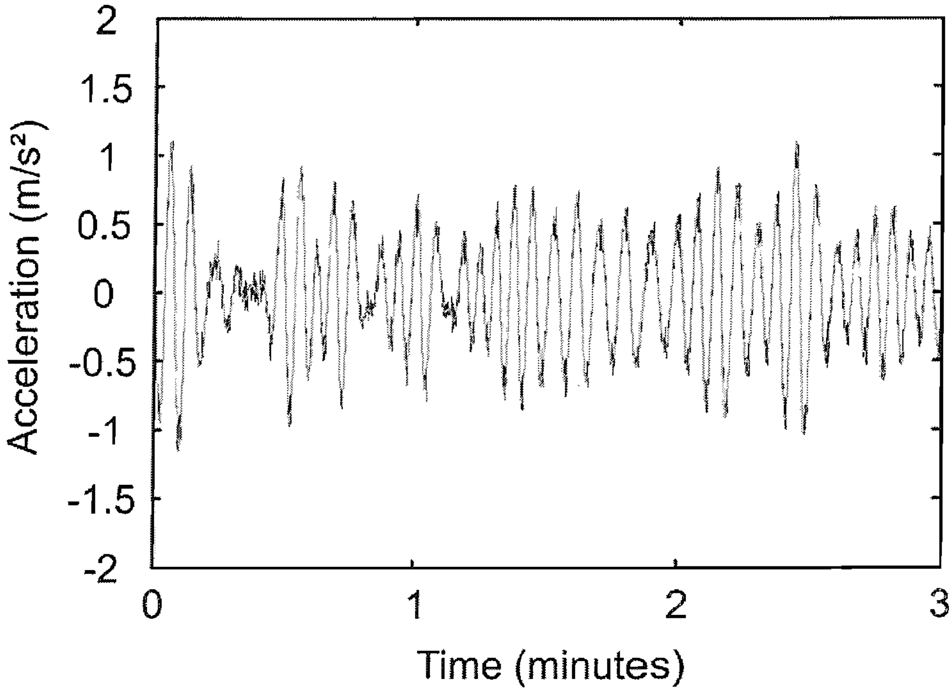


Figure 5.2 Acceleration time series from a selected three minute period of the random motion waveform. Thick grey solid line = desired acceleration; thin black solid line = measured acceleration.

5.3 RESULTS

5.3.1 Motions

Figure 5.2 compares a three minute time history segment from the desired acceleration and the corresponding segment from a measured time history randomly selected from the subject exposures. The error in the root-mean-square acceleration was calculated as the ratio of the difference between the desired and measured root-mean-square accelerations and the desired root-mean-square acceleration. Four subjects terminated the random motion waveform condition before reaching 30-minutes. Of the 13 subjects completing the condition, the error in the root-mean-square acceleration exposure was less than 1.6%.

Acceleration power spectral densities were calculated for the 13 measured 30-minute exposures and compared to the desired power spectral density (Figure 5.3). Comparisons between the desired and measured time histories and power spectral densities illustrate the accuracy of the motion simulation as suggested by the low root-mean-square acceleration error.

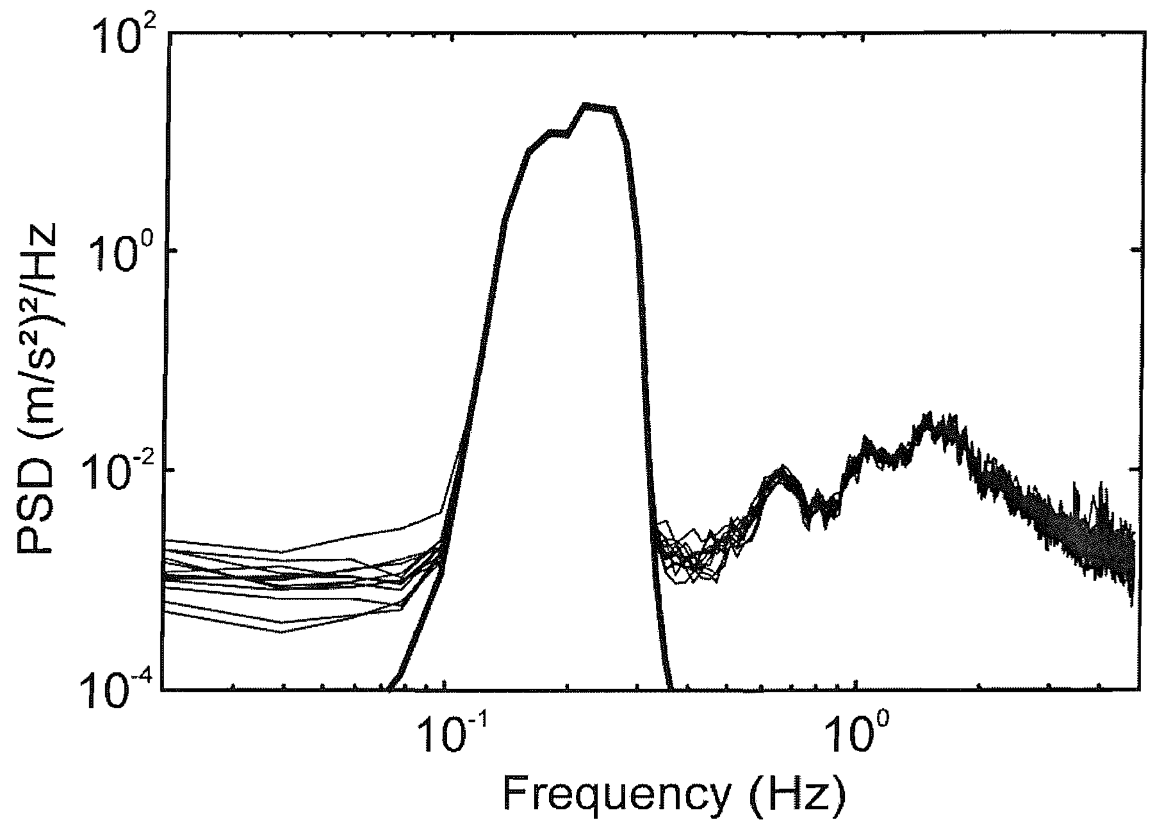


Figure 5.3 Acceleration power spectral densities (PSD) of the random motion waveform (Thin black lines = measured PSD; Thick black line = desired PSD).

5.3.2 Matching subjects

A total of 17 subjects were exposed to the octave-band random motion. When combined with the two groups of subjects studied previously, the three independent groups were matched to each other for the six measures of self-rated motion sickness susceptibility: illness susceptibility in transport in the last year, $I_{susc(yr)}$ (χ^2 = 0.257, p = 0.879); vomiting susceptibility in the last year, $V_{susc(yr)}$ (χ^2 = 1.296, p = 0.523); total susceptibility to vomiting, V_{total} (χ^2 = 0.098, p = 0.952); total susceptibility to motion sickness, M_{total} (χ^2 = 4.689, p = 0.096); total susceptibility to motion sickness on land transport, M_{land} (χ^2 = 4.209, p = 0.122); and total susceptibility to motion sickness on non-land transport, $M_{non\text{-}land}$ (χ^2 = 2.029, p = 0.363).

There was a significant age difference (p = 0.031) between subjects. The mean ages and standard deviations for the sinusoidal, random and stationary conditions were 20.58 and ±2.07 years, 22.41 and ±1.97 years, and 21.25 and ±1.73 years respectively.

5.3.3 Illness ratings

Figure 5.4 shows the proportion of subjects in each condition reporting each illness rating. When compared to the motion sickness reported with sinusoidal oscillation, random oscillation caused a slightly greater proportion of subjects to report each illness rating. The mean illness ratings reported at each minute by the subjects in each condition increased over the 30-minute period of exposure (Figure 5.5). The mean illness ratings varied between 0 ("No symptoms") and 2 ("Mild symptoms, e.g. stomach awareness but no nausea") for the non-stationary conditions but remained well below 1 ("Any symptoms, however slight") for the stationary condition.

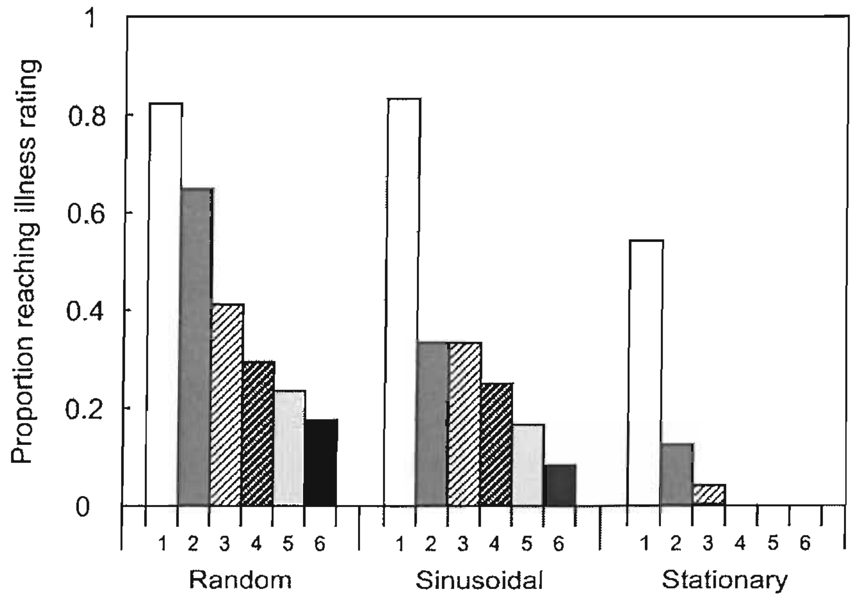


Figure 5.4 Proportion of subjects to reach each illness rating (1 to 6) with each type of motion waveform.

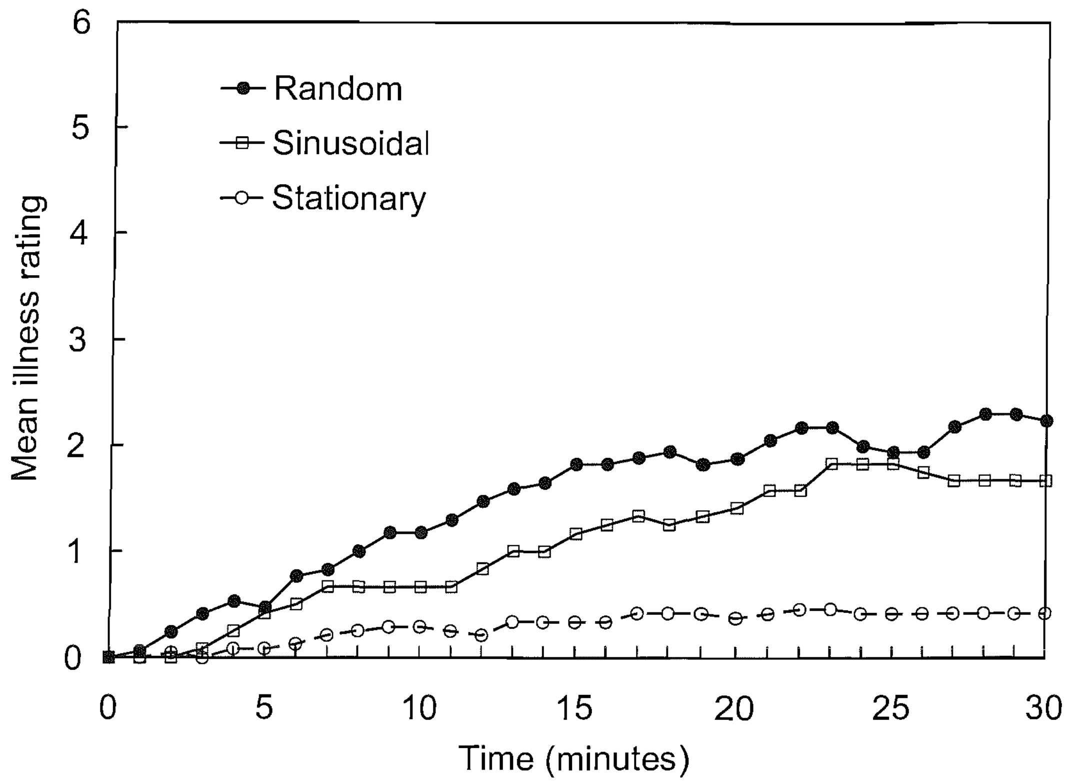


Figure 5.5 Mean illness ratings during 30-minute exposures to lateral motion and during a static condition.

5.3.4 Effect of motion waveform

When compared at each minute of the 30-minute exposure, there were no significant differences ($p > 0.05$) between the illness ratings reported by the subjects in the random and sinusoidal waveform conditions. A Kruskal-Wallis independent samples test found a significant difference between the average illness ratings reported in the three conditions ($p = 0.004$). Figure 5.6 shows the median average illness ratings reported during the exposures, whilst Table 5.1 provides the results of paired comparisons: the average illness ratings show a significant difference between the sinusoidal and stationary waveforms and a highly significant difference between the random and stationary waveforms. There was no significant difference in the average illness ratings reported by the groups of subjects exposed to the sinusoidal waveform and random motion waveforms.

Table 5.1 Values of p for the difference between total illness ratings of paired motion waveform conditions (Mann-Whitney U test) * significant, $p < 0.05$, ** highly significant, $p < 0.01$

Motion Condition	Sinusoidal	Octave-band random
Stationary	0.022*	0.002**
Sinusoidal		0.527

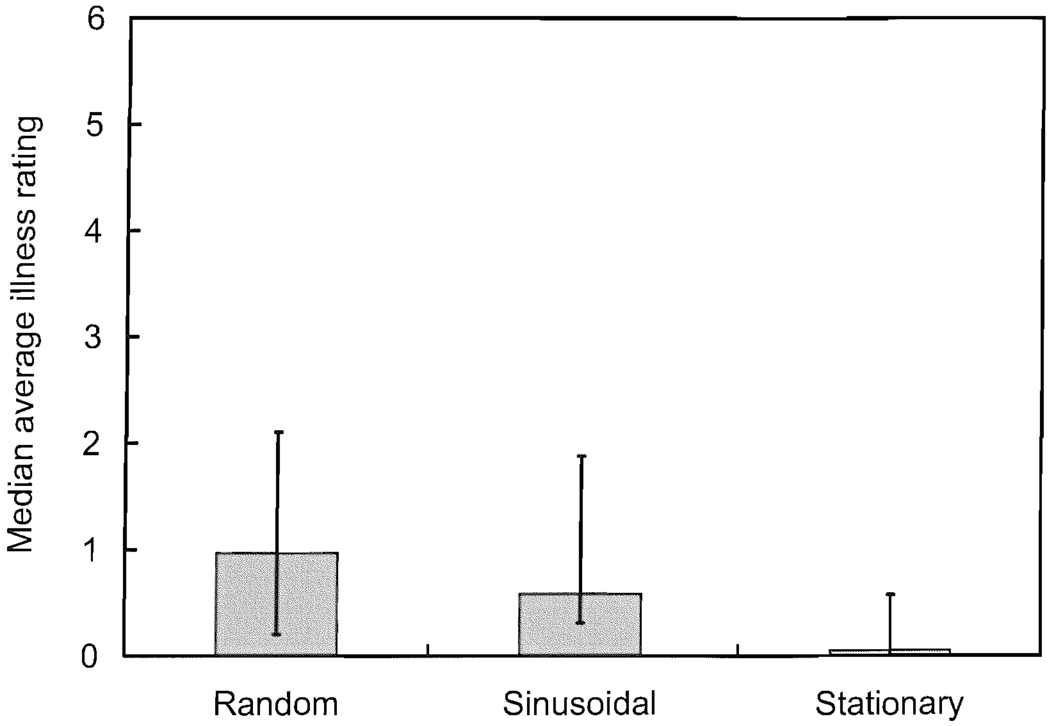


Figure 5.6 Median average illness ratings for the random, sinusoidal and stationary conditions (lower and upper error bars indicate 25th and 75th percentiles respectively).

5.3.5 Self-ratings of motion sickness susceptibility

Various measures of self-rated motion sickness susceptibility were compared to the average illness ratings reported during exposure to the sinusoidal and random waveform conditions. Subject self-ratings of total susceptibility to motion sickness were positively correlated with their average illness ratings (Spearman: r = 0.401, $p < 0.05$). The questionnaire responses from subjects thus indicated how they would feel when they were later exposed to horizontal motion in the laboratory.

The self ratings of motion sickness susceptibility were divided into two categories of transport: land transport (car, bus, coach and train) and non-land transport (small boat, ship and aeroplane). Marginally significant positive correlations of the average illness ratings reported in the laboratory were found with the subjects self rated susceptibility for land transport (Spearman: r = 0.356, $p = 0.058$) and the self-rated susceptibility for non-land transport (Spearman: r = 0.348, p = 0.065).

There was a negative but insignificant correlation of age with respect to the average illness ratings (Spearman: r = -0.128, $p = 0.509$).

5.3.6 Symptoms

Over all three conditions, there was no significant difference between the total symptom scores reported by subjects in the three conditions (Kruskal-Wallis $\chi^2 = 1.911$, $p = 0.385$). However, there was a highly significant positive correlation between the total number of symptoms and the average illness ratings (Spearman: $r = 0.831$, $p < 0.001$).

5.4 DISCUSSION

5.4.1 Effect sizes, number of subjects and statistical power

Post hoc calculation of power

The statistical power of the paired comparison between the average illness ratings reported with the octave-band random and the sinusoidal motion waveforms was estimated. For these calculations, it was necessary to assume that a *t*-test was used to compare the means observed with two independent groups with common variance. A two tailed test with a significance criterion of 0.05 was assumed.

The power was calculated using the SamplePower program (version 1.20, 1997; SPSS Inc.). Details of the parameters and assumptions used in the analysis are given in Appendix H: when the mean difference was estimated as 0.42, the sample standard deviation estimated at 1.424 and the degrees of freedom were 27, the statistical power was estimated as 12%.

Effect size

To estimate the number of subjects required in future studies, it is necessary to define the size of the effect that it is important to detect. In this case the effect of interest is the mean difference in average illness ratings reported between conditions. In the experiments performed here a seven-point illness rating scale is used (see Chapter 4).

It can be assumed that the smallest effect size of importance would be a difference in average illness rating ranging between 1.0 and 1.5. Any smaller mean difference in average illness ratings would not prove substantive as the rating scale cannot discriminate smaller differences. An effect of this magnitude could be anticipated with this illness rating scale (e.g. when comparing the sinusoidal or octave-band random motion waveform conditions to the stationary condition).

Number of subjects

Given a desired statistical power, the expected variance and the type of test, the number of subjects required to find a significant substantive effect can be calculated. SamplePower was used to tabulate the number of subjects corresponding to a given power for two effect sizes, 1.0 and 1.5, assuming a significance criterion of 0.05 and a standard deviation in average illness rating equal to 1.42. The respective tables are shown in Table 5.2 and Table 5.3.

In determining an appropriate sample size, the convention is to aim for a statistical power of 80%. Therefore, assuming a standard deviation of 1.42 and given a difference in average illness ratings of 1.0, 33 subjects would be required in each condition for the result to be statistically significant. If, however, the effect size was 1.5, only 16 subjects would be required.

It is assumed that 20 subjects per condition would be sufficient to find substantive and realistic significant differences in average illness ratings.

5.4.2 Effect of waveform

The mean illness ratings reported during the 30-minute exposures to motion were low: the mean illness ratings remained below an illness rating of 3 ("Mild nausea").

The results suggest that, when centred at the same frequency with the same root-mean-square acceleration magnitude, there is not a substantial difference in the average illness ratings reported with sinusoidal or octave-band random motions; however, the statistical power of the experiment was low (12 to 56%), such that it is at least equally likely that a significant difference could not have been found with the observed effect size and variance. A finding of no significant difference would be consistent with Guignard and McCauley (1982), who found for three out of four conditions that motion sickness incidence (defined as the proportion of subjects vomiting) did not vary significantly with waveform.

The finding that subjects' responses on the motion sickness susceptibility questionnaire were correlated with their average illness ratings achieved in the experiment suggests that the motions investigated may be relevant to motion sickness occurrence in the real-world.

Table 5.2 Sample size and statistical power for a mean difference in average illness ratings equal to 1.0, a statistical significance 0.05 and a standard deviation 1.42.

N (per condition)	Power
10	0.320
11	0.349
12	0.378
13	0.407
14	0.434
15	0.461
16	0.487
17	0.513
18	0.537
19	0.561
20	0.583
21	0.605
22	0.626
23	0.646
24	0.666
25	0.684
26	0.702
27	0.719
28	0.735
29	0.750
30	0.765
31	0.779
32	0.792
33	0.804
34	0.816
35	0.827
36	0.838
37	0.848
38	0.858
39	0.867
40	0.875
41	0.883
42	0.890
43	0.898
44	0.904
45	0.910
46	0.916
47	0.922
48	0.927
49	0.932
50	0.937
51	0.941
52	0.945
53	0.949
54	0.952
55	0.955

Table 5.3 Sample size and statistical power for a mean difference in average illness ratings equal to 1.5, a statistical significance 0.05 and a standard deviation 1.42.

N (per condition)	Power
10	0.608
11	0.654
12	0.696
13	0.734
14	0.767
15	0.797
16	0.824
17	0.848
18	0.868
19	0.886
20	0.902
21	0.916
22	0.928
23	0.939
24	0.948
25	0.955
26	0.962

5.4.3 Frequency weightings

If it were assumed that there was no significant difference in motion sickness between motion waveform conditions then weightings derived from measurements using sinusoidal stimuli in the laboratory might be applicable to motions measured in transport, where the motions are usually random and rarely purely sinusoidal.

Specifically, it is hypothesised that the acceleration occurring within an octave-band frequency range can be evaluated using a weighting gain calculated from the motion sickness reported with harmonic oscillation at an equivalent acceleration magnitude and octave band centre frequency.

5.5 CONCLUSIONS

Significant differences in the amount of sickness produced by sinusoidal and random motion waveforms were not observed; although, the experiment may have been insensitive to differences due to a low statistical power. Findings based on a conclusion of no significant difference in waveform would be consistent with those from an earlier study.

CHAPTER 6 LATERAL OSCILLATION: EFFECT OF FREQUENCY

6.1 INTRODUCTION

The study reported in this chapter formed the first part of a series of motion sickness experiments investigating the effects of the frequency and the relative magnitude of combined lateral and roll oscillations. The aim of this investigation was to study the effect on motion sickness of Earth-horizontal lateral motion with oscillations in the frequency range from 0.0315 to 0.8 Hz.

A review of literature (Chapter 2) established that oscillation frequency has an effect on the susceptibility to motion sickness with vertical and horizontal translational motion (Lawther and Griffin, 1987; Golding *et al.* 2001; Griffin and Mills, 2002a). The review also established the lack of data pertaining to the effect on motion sickness of oscillation frequencies below 0.2 Hz: only two laboratory conditions have studied fore-and-aft and vertical oscillations with frequencies below 0.16 Hz, whilst there have been no laboratory studies with lateral oscillation at frequencies below 0.2 Hz.

An acceleration frequency weighting has been developed to represent the dependence of motion sickness on the frequency of vertical oscillation. The weighting is defined as weighting W_f in British Standard 6841:1987 (British Standards Institution, 1987) and International Standard 2631-1:1997 (International Organization for Standardization, 1997b). One uncertainty associated with the weighting W_f is the frequency-dependence of motion sickness at frequencies less than about 0.1 Hz.

An acceleration frequency weighting for either fore-and-aft oscillation or lateral oscillation has not been proposed; although, a study of constant peak velocity (±0.5 m/s) lateral oscillations at frequencies above 0.2 Hz (Griffin and Mills, 2002a) found that motion sickness was independent of frequency. The authors suggested an acceleration frequency weighting for lateral motions might have a gain approximately inversely proportional to frequency.

Fore-and-aft and lateral accelerations were reported to be responsible for motion sickness in road transport and there are significant horizontal accelerations at frequencies less than 0.2 Hz in both road and rail transport. However, in these environments, the utility of frequency weighting W_f is uncertain: Turner and Griffin (Turner and Griffin, 1999b) reported that the W_f frequency weighting did not give good predictions of the incidence of motion sickness in road coaches and Griffin and Newman (Griffin and Newman, 2004) suggested that it was not optimum for predicting sickness in cars.

In order to assist the prediction of sickness in road and rail transport, this study has the objective of investigating whether or not an acceleration frequency with a gain inversely proportional to frequency is suitable for lateral oscillations: i) by identifying the frequency effect of lateral oscillation at frequencies below 0.2 Hz; and ii) by examining lateral oscillation at frequencies above 0.2 Hz, but with lower acceleration magnitudes than used in a previous study (i.e. Griffin and Mills, 2002a). Subjects were matched to those used in a stationary condition in the previous study (Griffin and Mills, 2002a), such that the results could be compared.

Specifically, two related hypotheses are tested: i) with constant peak velocity lateral oscillations in the range 0.0315 to 0.2 Hz, motion sickness will be independent of frequency; and ii) with constant peak jerk lateral oscillations in the range 0.315 to 0.8 Hz, motion sickness will be inversely proportional to the square of the frequency.

6.2 MOTIONS

An objective of these studies was to use motion magnitudes relevant to those experienced by passengers in tilting-trains: octave-band analysis of the Earth-lateral accelerations measured in the passenger coach of a tilting-train (Chapter 3) determined that the root-mean-square magnitudes remained below 1.0 m/s² in the frequency range from 0.016 to 1.0 Hz.

The choice of motions that were selected for the experiment was limited by the dynamic response of the motion simulator. With lateral oscillations at frequencies below about 0.1 Hz, the response of the horizontal motion simulator (see Chapter 4) was limited by displacement (±6 m), whereas with oscillation frequencies above 0.1 Hz the response was limited by acceleration (±2 m/s²). Furthermore, the choice of motion conditions was limited by consideration of the motions to be studied in subsequent experiments: in these experiments, the intention was to use the same Earth-lateral motion magnitudes, but with the addition of roll (see Chapter 7). The roll-rig was limited by roll velocity (±11.5 °/s) in the frequency range from 0.2 to 0.8 Hz, such that if equivalent lateral motions were to be used in both studies, over this range the Earth-lateral oscillations had an equivalent limitation in jerk (±1.96 m/s³).

In order to test the desired experimental hypotheses, it was convenient to choose constant peak velocity (±1.0 m/s) oscillations in the frequency range from 0.0315 to 0.2 Hz and constant peak jerk (±1.96 m/s³) oscillations in the frequency range from 0.315 to 0.8 Hz. These motions fulfilled the above constraints, such that they were relevant to tilting-train motions and they did not exceed the limitations of the motion simulator. The motion parameters for the nine lateral oscillation conditions are detailed in Table 6.1.

Table 6.1 Lateral oscillation motion parameters.

Frequency	Peak Earth-lateral displacement	Peak Earth-lateral velocity	Peak Earth-lateral acceleration	Peak Earth-lateral jerk	Root-mean-square Earth-lateral acceleration
(Hz)	(m)	(ms^{-1})	(ms^{-2})	(ms^{-3})	(ms^{-2} r.m.s)
0.0315	± 5.05	± 1.00	± 0.20	± 0.04	0.14
0.05	± 3.18	± 1.00	± 0.31	± 0.10	0.22
0.08	± 1.99	± 1.00	± 0.50	± 0.25	0.36
0.125	± 1.27	± 1.00	± 0.79	± 0.62	0.56
0.16	± 0.99	± 1.00	± 1.01	± 1.01	0.71
0.20	± 0.80	± 1.00	± 1.26	± 1.58	0.89
0.315	± 0.25	± 0.50	± 0.99	± 1.96	0.70
0.5	± 0.06	± 0.20	± 0.62	± 1.96	0.44
0.8	± 0.02	± 0.08	± 0.39	± 1.96	0.28

6.3 RESULTS

6.3.1 Subjects

For each of the six measures of motion sickness susceptibility, the nine groups of subjects were matched (using a Kruskal-Wallis test) to each other and to those used in a previous study involving a stationary condition (Griffin and Mills, 2002a): illness susceptibility in transport in the last year, $I_{susc(yr)}$ (χ^2 = 16.462, p = 0.058); vomiting susceptibility in transport in the last year, $V_{susc(yr)}$ (χ^2 = 10.837, p = 0.287); total susceptibility to vomiting in transport, V_{total} (χ^2 = 9.916, p = 0.357); total susceptibility to motion sickness in transport M_{total} (χ^2 = 10.302, p = 0.327); total susceptibility to motion sickness on land transport M_{land} (χ^2 = 9.268, p = 0.413); and total susceptibility to motion sickness on non-land transport $M_{non\text{-}land}$ (χ^2 = 10.233, p = 0.333).

6.3.2 Illness ratings

Over all conditions, 12% (22/120) of the subjects did not report any symptoms ("0: no symptoms") at any time during motion exposure, whilst 7% (12/180) of the subjects terminated the experiment by reporting the highest illness rating ("6: moderate nausea and want to stop"). The proportions of subjects reaching each illness rating within each condition are shown in Figure 6.1.

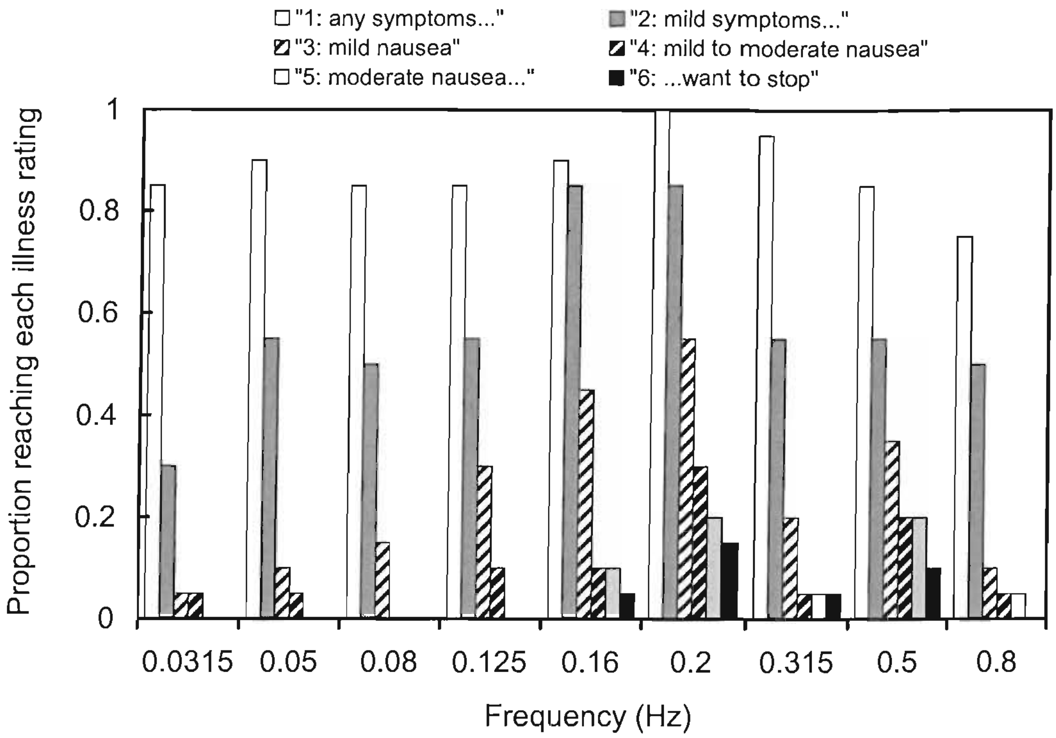


Figure 6.1 Proportion of subjects to reach each illness rating (1 – 6) at each frequency.

The mean illness ratings, calculated at each minute across the 20 subjects within each condition, increased over the initial 10 or 20 minutes of the 30-minute exposures (Figure 6.2).

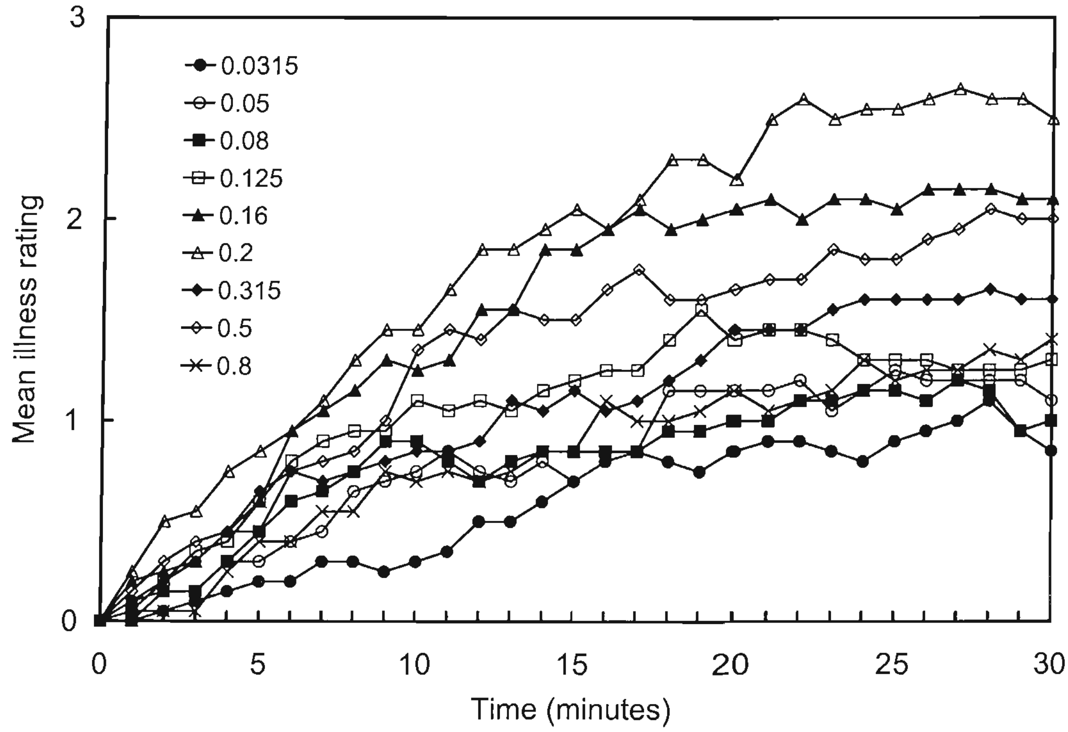


Figure 6.2 Mean illness ratings at each minute of exposure for each frequency of oscillation.

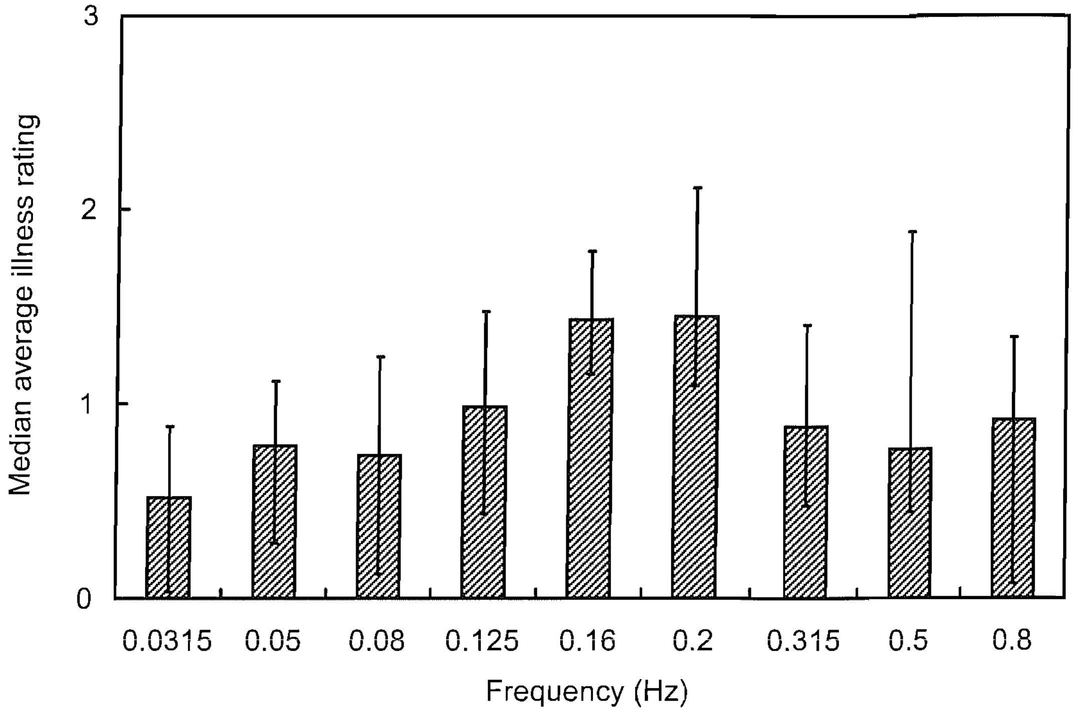


Figure 6.3 Median average illness ratings reported with each frequency of oscillation. Error bars indicate 25th and 75th percentiles.

Average illness ratings were calculated for each subject. The median average illness ratings were found for each condition and are shown in Figure 6.3. Over the nine frequencies of oscillation, there were highly significant differences (Kruskal-Wallis: χ^2 = 25.313, $p < 0.01$) in the average illness ratings reported by subjects.

6.3.3 Illness ratings with oscillation in the frequency range from 0.0315 to 0.2 Hz

There were significant differences in the average illness ratings reported by subjects exposed to lateral oscillations having constant peak velocity (Kruskal-Wallis: χ^2 = 24.403, $p < 0.01$). Paired comparisons showed that the average illness ratings increased significantly with increasing frequency over the frequency range from 0.0315 to 0.2 Hz (Mann-Whitney U-test: $p < 0.05$ between 0.08 and 0.16 Hz, 0.125 and 0.2 Hz; $p < 0.01$ between 0.0315 and 0.16Hz, 0.0315 and 0.2 Hz, 0.05 and 0.16 Hz, 0.05 and 0.2 Hz, 0.08 and 0.2 Hz); however, there were no significant differences between the average illness ratings reported by subjects exposed to oscillation at 0.16 Hz and 0.2 Hz (p = 0.779).

6.3.4 Illness ratings with oscillation in the frequency range from 0.315 to 0.8 Hz

When subjects were exposed to constant peak jerk lateral oscillations at frequencies in the range from 0.315 to 0.8, no significant differences were found (Kruskal-Wallis: χ^2 = 1.128, $p < 0.569$).

6.3.5 Comparison of illness ratings to those reported in a static condition

The mean illness ratings at each frequency were compared with those previously obtained in a static condition in a study by Griffin and Mills (Griffin and Mills, 2002b). In the static condition, 24 subjects were exposed with an experimental environment and method matched to the present conditions but with no motion; the subjects were not informed that the cabin was not moving. There was a significant difference between the average illness ratings reported in the nine lateral oscillation conditions of the present experiment and the previous static condition ($\chi^2 = 44.832$, $p < 0.01$). There were also higher average illness ratings reported by subjects exposed to each lateral oscillation than those who experienced the static condition (Mann-Whitney U-test: $p < 0.05$ at 0.0315 and 0.8 Hz; $p < 0.01$ at 0.05, 0.08, 0.125, 0.16, 0.2, 0.315 and 0.5 Hz).

6.4 COX REGRESSION ANALYSIS

6.4.1 Dependent and independent variables

Cox regression analysis (see Chapter 4) was used to relate the exposure duration required to report a given illness rating to the frequency of oscillation and the self-reported motion sickness susceptibility. The data from a static condition, reported by Griffin and Mills (Griffin and Mills, 2002b), were included such that the results could be compared to the Cox regression analyses of the effects of frequency and magnitude of oscillation on motion sickness undertaken for previous studies (Griffin and Mills, 2002a; Griffin and Mills, 2002b). Three separate analyses were performed, one for each of three illness ratings: "1 – Any symptoms, however slight"; "2 – Mild symptoms, e.g. stomach awareness, but not nausea"; and "3 – Mild nausea".

The variables age, frequency, $I_{susc(yr)}$, $V_{susc(yr)}$, V_{total}, $\log_{10}(M_{total}+3)$, $\log_{10}(M_{land}+3)$ and $\log_{10}(M_{non\text{-}land}+3)$ were considered for entry into the Cox regression model. The variables frequency and each of the six motion sickness susceptibility measures were entered in turn into the model and the variables giving the best overall fit (based on the chi-square statistic) were selected. In order to improve their distribution, the variables M_{total}, M_{land} and $M_{non\text{-}land}$ were logarithm (base 10) transformed prior to analysis (a constant of 3 was first added to avoid taking the logarithm of negative or zero values). The following variables were transformed to categorical variables prior to being entered into the Cox regression analysis[11]: frequency, $I_{susc(yr)}$ (4 categories: 0, $0 < I_{susc(yr)} \leq 0.120$, $0.120 < I_{susc(yr)} \leq 0.683$,

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[11] Prior to transformation into categorical variables, the $I_{susc(yr)}$, $V_{susc(yr)}$, and V_{total} categories were determined using the 'visual bander' function supplied in the SPSS statistical software package (SPSS; version 12.0, SPSS, Chicago, IL). The cut-points between categories were selected automatically to be the 25th, 50th and 75th percentiles. To form variable categories that would be

0.683 < $I_{susc(yr)}$ ≤ 1.67), $V_{susc(yr)}$ (3 categories: 0, 0 < $V_{susc(yr)}$ ≤ 0.167, 0.167 < $V_{susc(yr)}$ ≤ 1.67), and V_{total} (4 categories: 0, 1, 2 ≤ V_{total} ≤ 6, 7). The reference conditions for all the categorical variables entered into the model were the zero conditions (i.e. the cases when the variable of interest was 0).

6.4.2 Results

Table 6.2 gives the exponents of the regression coefficients and statistical significance for the variables remaining in each of the Cox regression models. All three analyses discarded the variables age, $I_{susc(yr)}$, $V_{susc(yr)}$, V_{total}, $\log_{10}(M_{land}+3)$ and $\log_{10}(M_{non\text{-}land}+3)$ from the model. These measures of motion sickness susceptibility did not significantly improve the predictive properties of the model.

The change in risk associated with a unit change in $\log_{10}(M_{total}+3)$ ranged between about 3 or 4 depending on the event of interest. So, for example, a subject reporting an M_{total} of 7 ($\log_{10}(M_{total}+3)$ = 1) would be three to four times more likely to report an illness rating of "1", "2" or "3" than a subject reporting an M_{total} of -2 (i.e. $\log_{10}(M_{total}+3)$ = 0).

Table 6.2 Cox regression models for illness ratings "1" to "3".

Illness rating of interest:	*"1 – any symptoms ..."*		*"2 – mild symptoms ..."*		*"3 – mild nausea"*	
Overall:	χ^2 = 50.681, p < 0.01		χ^2 = 66.743, p < 0.01		χ^2 = 40.813, p < 0.01	
Variable	Exp(ß)	p	Exp(ß)	p	Exp(ß)	p
Frequency:	---	< 0.01**	---	< 0.01**	---	< 0.01**
0.0315 Hz	2.66	< 0.01**	3.13	0.108	1.41	0.809
0.05 Hz	3.72	< 0.01**	7.49	< 0.01**	3.18	0.346
0.08 Hz	3.35	< 0.01**	7.11	< 0.01**	4.92	0.169
0.125 Hz	5.37	< 0.01**	10.06	< 0.01**	10.80	0.028*
0.16 Hz	5.23	< 0.01**	20.79	< 0.01**	16.38	< 0.01**
0.2 Hz	6.61	< 0.01**	15.74	< 0.01**	20.40	< 0.01**
0.315 Hz	5.70	< 0.01**	9.34	< 0.01**	7.27	0.078
0.5 Hz	3.94	< 0.01**	9.40	< 0.01**	13.23	0.016*
0.8 Hz	2.42	0.021*	7.64	< 0.01**	3.28	0.334
$\text{Log}_{10}\ M_{total}$	3.01	< 0.01**	4.31	< 0.01**	3.22	0.018*

The variable 'Frequency' was entered as a categorical variable in the analysis with the static condition as the reference condition. * = p < 0.05; ** = p < 0.01.

consistent across all investigations, the categorical variable transformation was applied to all 23 conditions reported in this thesis.

Statistically, the frequency of oscillation had a highly significant influence on the occurrence of subjects reporting each of the three illness ratings. When the event of interest was a reported illness rating of "1", the relative risk (i.e. the risk relative to the static condition) was highly significant at each frequency of oscillation (ranging from 2.42 with oscillation at 0.8 Hz to 6.61 with oscillation at 0.2 Hz). With an illness rating of "2", the relative risks (ranging from 3.13 at 0.0315 Hz to 20.79 with 0.16 Hz) were highly significant for all frequencies except 0.0315 Hz. With this model, oscillation at 0.16 Hz was associated with a greater risk (20.79) than oscillation at 0.2 Hz (15.74). The risks of reporting "3 – mild nausea" (ranging from 1.41 at 0.0315 Hz to 20.40 at 0.2 Hz) were significantly related to the frequency of oscillation at 0.125, 0.16, 0.2 and 0.5 Hz.

With constant peak velocity oscillations in the frequency range up to about 0.16 or 0.2 Hz, the risks of reaching each illness rating tended to increase with increasing oscillation frequency. Above 0.2 Hz the risk of reaching each illness tended to decrease with increasing frequency.

6.5 DISCUSSION

6.5.1 Illness ratings

With the lateral oscillation conditions studied here, neither comparison of the average illness ratings nor the Cox regression models support the hypothesis that the reports of motion sickness could be explained by an acceleration frequency weighting with a gain inversely proportional to frequency.

With oscillation at constant peak velocity over the frequency range 0.0315 to 0.2 Hz, the average illness ratings reported by the subjects increased with increasing frequency and, therefore, increased acceleration magnitude. This is consistent with motion sickness being predicted by an acceleration frequency weighting with constant gain, but the absence of a significant difference between the average illness ratings at 0.16 Hz and 0.2 Hz, despite the increase in acceleration between the two conditions, suggests a tendency towards a dependence on velocity in the region of 0.2 Hz. The Cox regression analysis was consistent with this observation, showing an increase in relative risk (compared to a static condition) with increasing frequency when the motions had the same peak velocity.

Paired comparisons of the average illness ratings reported with constant peak jerk oscillations over the frequency range from 0.315 to 0.8 Hz, found that motion sickness did not change significantly, suggesting an acceleration frequency weighting with a gain proportional to frequency. In contrast, Cox regression found that over this frequency range the risks of reaching illness ratings "1", "2" and "3" (relative to a stationary condition) decreased significantly with increasing frequency, suggesting an acceleration frequency weighting with a gain proportional to acceleration or velocity. The contradictory findings are explained if the groups of subjects had sufficiently large variance in average illness ratings, relative to any differences between the groups, such that the statistical power was insufficient to substantiate the hypothesis that there was no difference between the average illness ratings in these groups.

6.5.2 Lateral acceleration frequency weighting

The frequency weighting defined for vertical oscillation, W_f, was based on the incidence of vomiting. In this study, vomiting did not occur and so some other measure, either the 'proportion of subjects reaching each illness rating', or the 'average illness rating', must be used. Of these, the proportion of subjects reaching an illness rating is most closely analogous to the incidence of vomiting and seems appropriate. This measure has the additional advantage that sensitivity and specificity can be optimised by selecting the illness rating most appropriate for degree of sickness caused by the range of stimuli investigated.

An acceleration frequency weighting for lateral oscillation was investigated using a combination of the results reported here and the motion sickness data obtained with lateral oscillation in previous experiments (Griffin and Mills, 2002a; Griffin and Mills, 2002b). The previous experiments investigated the effects of the frequency and magnitude of lateral oscillation on motion sickness at frequencies between 0.2 Hz and 0.8 Hz. Also included in the weighting, are data from another study in the series of studies conducted for this thesis (Chapter 8): this later study provides motion sickness data for lateral oscillation at 0.1 Hz. The subjects in the present studies were selected so that their motion sickness susceptibilities were matched to those of the subjects used in the earlier study with higher frequencies.

The frequency dependence of motion sickness caused by lateral oscillation was found by dividing the proportion of subjects who reached a given illness rating by the root-mean-square acceleration magnitude. This gives a frequency weighting, and is equivalent to the 'normalised vomiting' procedure used to determine the frequency weighting W_f for vertical oscillation (Lawther and Griffin, 1987). The validity of this operation depends on the assumption that the effect of acceleration magnitude on motion sickness is linear (i.e. doubling the magnitude will double the motion sickness).

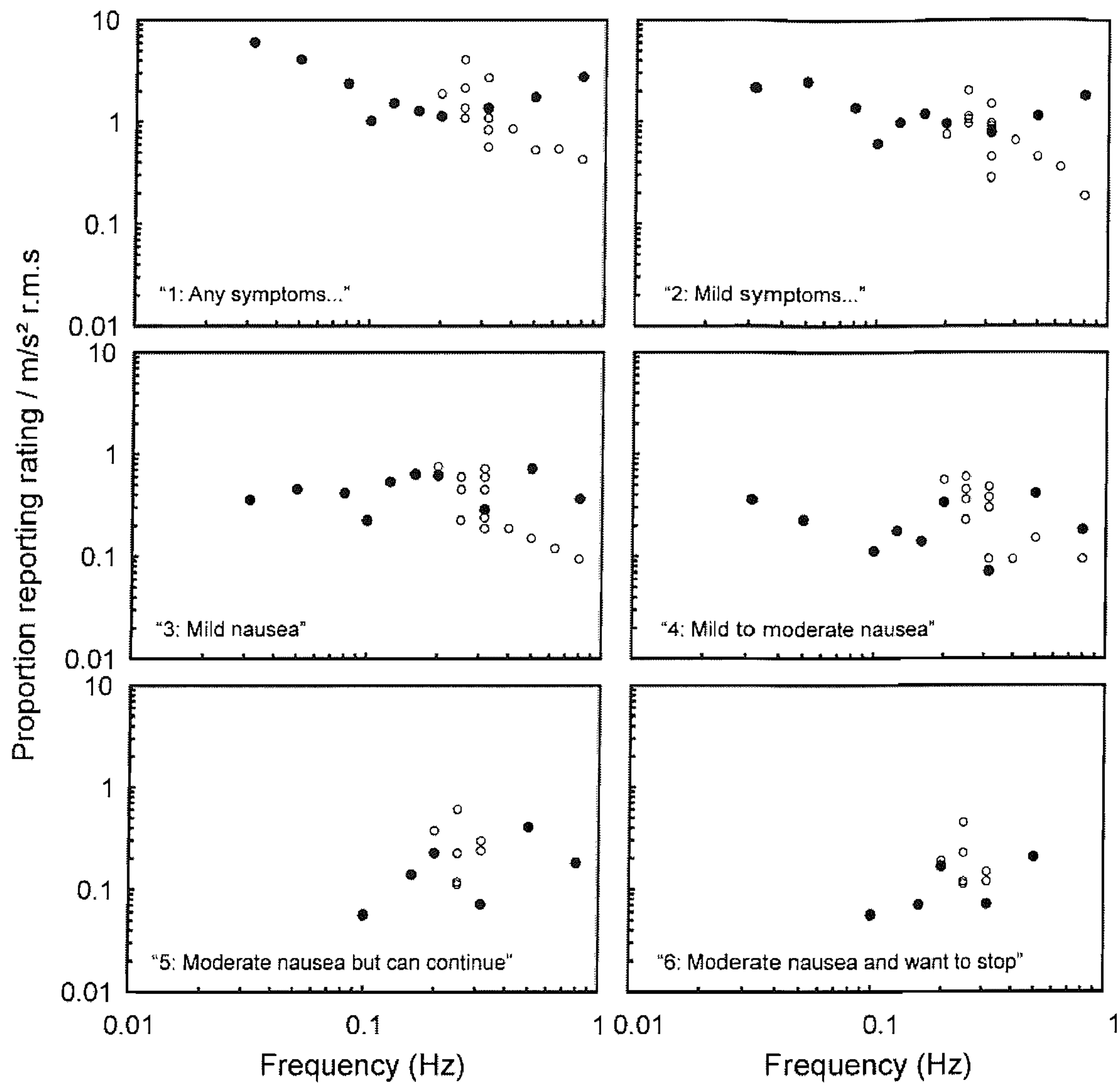

Figure 6.4 Proportion of subjects reporting an illness rating (1 – 6) divided by the root-mean-square acceleration at each frequency of oscillation. Closed circles = data from the studies of lateral oscillation reported in this thesis; open circles = data from the experiments of Mills and Griffin (Mills and Griffin, 1998 and 2000; Griffin and Mills, 2002a, 2002b).

Figure 6.4 shows weightings formed from the proportions of subjects who reported illness ratings "1" to "6" at each frequency over the 30-minute exposures. In most conditions, most of the subjects reported an illness of at least *"1 – any symptoms, however slight"*, so the proportion reaching this rating does not discriminate between the frequencies of oscillation: although the proportion to reach this rating appears to imply that over the frequency range 0.0315 Hz to 0.2 Hz these motions were similar (and therefore the velocity of motion was the determining factor), the Cox regression shows that this level of sickness was reached later for low frequencies than for high frequencies. The frequency weighting cannot, therefore, be defined using the proportion of subjects who reached this low level of motion sickness. At the higher illness ratings, e.g. *"4 – mild to moderate nausea"* and above, there was no response at some frequencies (i.e. 0.08 and 0.63 Hz) and a low response at many other frequencies, so a frequency weighting cannot be fully defined with these ratings.

From the distribution of illness ratings in Figure 6.1, it may be expected that either the proportion of subjects who reached "2 - mild symptoms e.g. stomach awareness, but not nausea", or the proportion of subjects who reached "3 – mild nausea" would be appropriate for defining a frequency weighting. For these two illness ratings, there is a reasonable compromise between specificity and sensitivity and the level of sickness is of practical interest. However, the weightings derived from these measures differ, particularly at low frequencies (Figure 6.4). This implies that the proportion of subjects reaching these two illness ratings had different dependencies on the frequency of oscillation, as can be seen in Figure 6.1.

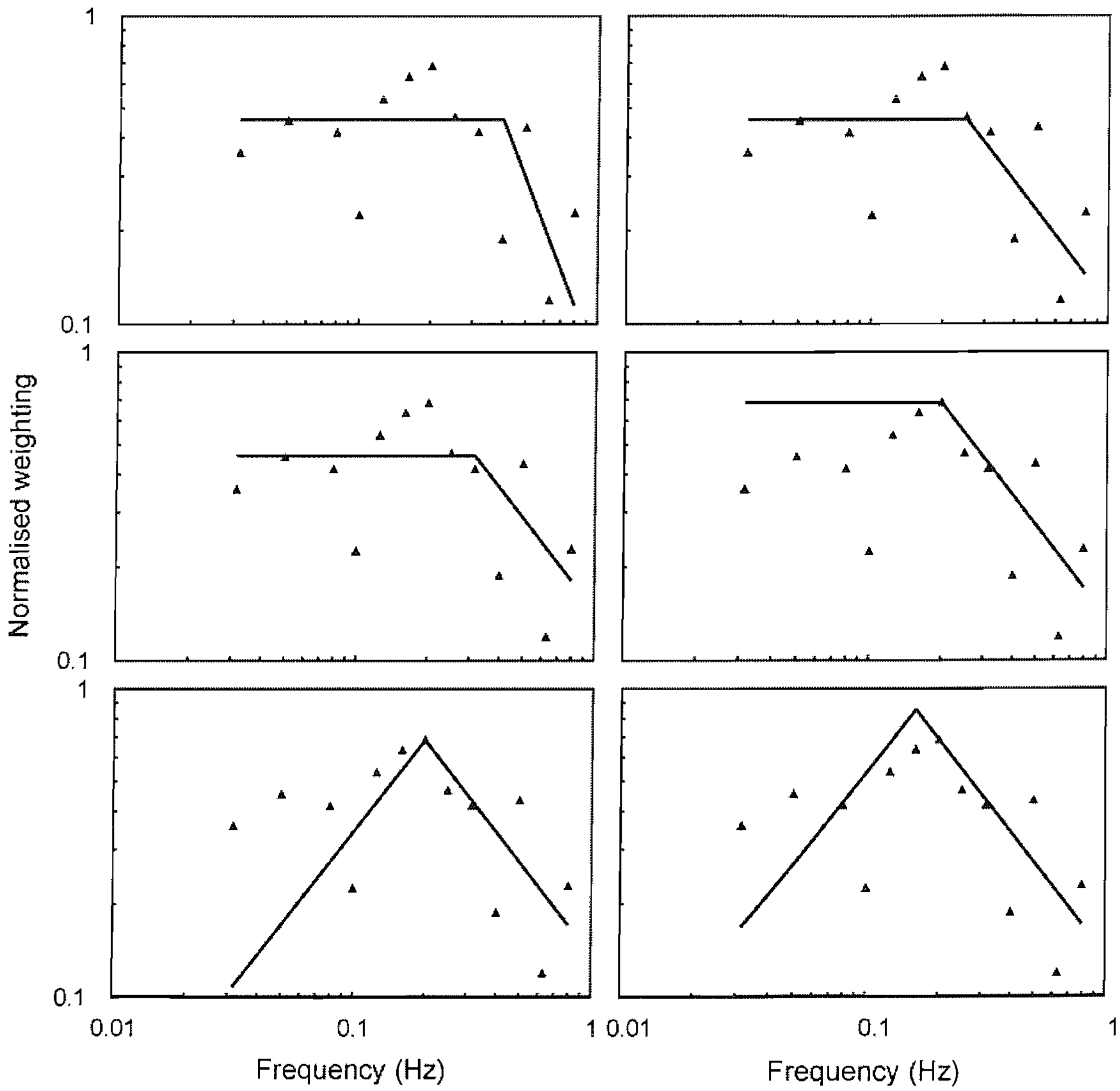

Figure 6.5 Alternative asymptotic acceleration frequency weightings for lateral oscillation compared to the normalised mild nausea incidence at each frequency (where more than one weighting point exists at any one frequency the average weighting has been taken).

For practical purposes the proportion of subjects reaching "3 – mild nausea" may be of greater interest and this rating was therefore chosen to calculate a 'normalised mild nausea incidence' (i.e. the proportion of subjects reaching "3 – mild nausea" divided by the root-mean-square acceleration) at each frequency in the range 0.0315 to 0.8 Hz. Where there was more than one data point for a frequency of oscillation (e.g. at 0.2 and 0.315 Hz), the average of the weightings calculated at each frequency was used. Various alternative asymptotic (i.e. straight line) acceleration frequency weightings are compared to the weighting data and shown in Figure 6.5. It is not clear which weighting best represents the real effect of frequency; however, one simple frequency weighting provides a reasonable fit to the data (Figure 6.5, top right pane) and suggests an acceleration weighting independent of frequency over the range 0.0315 to 0.25 Hz (i.e. an acceleration weighting with 0 dB/octave slope) and proportional to velocity in the range 0.25 to 0.8 Hz (i.e. an acceleration weighting with -6 dB/octave slope).

The acceleration frequency weightings predicted from previous data (Griffin and Mills, 2002a; Griffin and Mills, 2002b) can be compared to the data from the investigations reported in this thesis. It is noted that with oscillation at 0.2 and 0.315 Hz similar weightings were predicted by all studies; however with the weightings at 0.5 and 0.8 Hz, significant differences exist. These differences may have occurred by chance or because of differences in the susceptibilities of the subjects used or because the effect of acceleration magnitude is non-linear. To some extent, the motion sickness susceptibilities reported by the groups were controlled by matching them to a common condition (the stationary condition). Differences due to chance might be discounted as consistent trends are observed within studies: within the previous study, an acceleration frequency weighting with a gain inversely proportional to frequency was observed. Whereas the data from this study predicts an acceleration frequency weighting with a constant gain over the frequency range from 0.0315 to 0.8 Hz. It is possible that the effect of lateral acceleration magnitude is non-linear and this needs to be investigated further: in the previous study the acceleration magnitudes increased from 0.44 to 1.78 ms^{-2} r.m.s with increasing frequency in the range 0.2 to 0.8 Hz. For practical purposes linearity will be assumed and the complete set of data from both studies will be used to form a realisable acceleration frequency weighting for lateral oscillations.

Table 6.3 Parameters for a realisable lateral acceleration frequency weighting.

Band-limiting				a-v transition			Upward step				Gain
f_1	Q_1	f_2	Q_2	f_3	f_4	Q_4	f_5	Q_5	f_6	Q_6	K
0.02	$1/\sqrt{2}$	0.8	$1/\sqrt{2}$	∞	0.4	0.86	∞	1	∞	1	0.46

A realisable frequency weighting can be developed in the same form as other weightings, such as those in ISO 8041:2005 (International Organization for Standardization, 2005), using the product of transfer functions of two component filters (a band-limiting filter and an acceleration weighting). It will be assumed that the weighting has similar characteristics to frequency weighting W_f, with the exception that the high-pass and low-pass components of the band-limiting filter has corner frequencies at 0.02 and 0.8 Hz, reflecting the wider range of frequencies, with a Q of $1/\sqrt{2}$ and the upward step component of the weighting removed (achieved by setting the corner frequencies to infinity). The acceleration-velocity transition filter corner-frequency and the weighting gain were optimised by minimising the mean square error using a non-linear optimisation routine to obtain the filter characteristics in Table 6.3.

The realisable weighting for normalised mild nausea incidence is shown in Figure 6.6 and compared to the weighting for vertical oscillation, W_f (normalised to equal the weighting data point at 0.2 Hz) and the asymptotic weighting described above. One difference between the asymptotic weighting and the realisable weighting is that with oscillations above 0.25 Hz the former assumes that motion sickness is dependent on velocity, whilst the latter assumes that motion sickness is dependent on displacement.

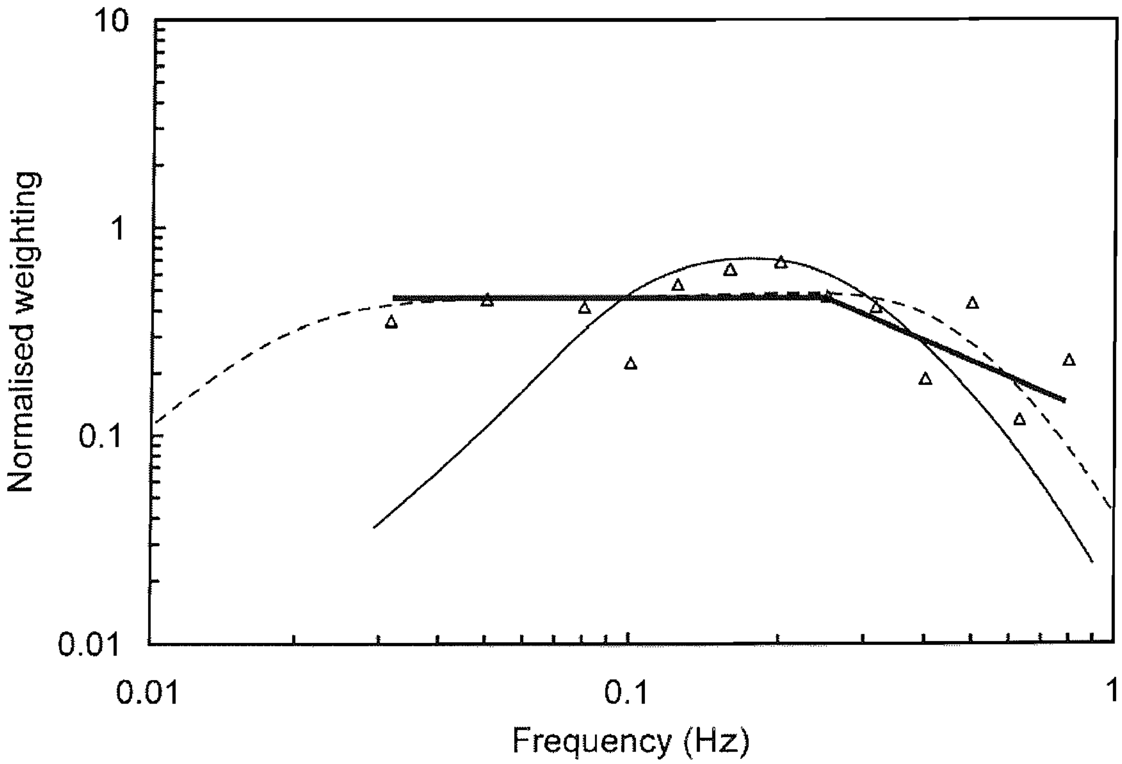

Figure 6.6 Asymptotic and realisable frequency weightings for lateral acceleration, derived from the normalised mild nausea incidence, compared to the weighting for vertical acceleration, W_f – as defined in BS 6841. Weighting W_f is normalised to equal the weighting data point at 0.2 Hz. Asymptotic weighting = solid thick line; realisable weighting = dotted line; normalised mild nausea incidence; W_f = solid thin line.

6.5.3 Comparison with motion in other axes

Horizontal oscillations

By calculating the time to reach "moderate nausea", Golding (Golding *et al.*, 2001) suggested a slope of -3 to -4 dB/octave to describe the frequency-dependence of motion sickness caused by fore-aft accelerations in the frequency range 0.2 to 0.4 Hz. This was broadly consistent with earlier estimates of -3.7 dB/octave with fore-aft oscillation in the range 0.205 to 0.5 Hz and -4.5 to -5.5 dB/octave with fore-aft oscillation in the range 0.25 to 1 Hz. In the range 0.1 to 0.2 Hz, a slope of 2 to 3 dB octave was suggested. These compare with slopes of -6 dB/octave and -12 dB/octave suggested for lateral oscillation by the asymptotic and realisable acceleration frequency weightings at frequencies above 0.25 Hz.

Griffin and Mills (Griffin and Mills, 2002a) suggested that an acceleration frequency weighting having a gain inversely proportional to frequency would provide a convenient simple method of evaluating lateral oscillation in the range 0.2 to 0.8 Hz. However, they noted that their results suggested a more complex weighting, reflecting decreased nauseogenicity at higher and lower frequencies. The slopes suggested with lateral and fore-aft oscillation were similar, with no significant differences between lateral and fore-aft oscillation at frequencies greater than 0.2 Hz (Griffin and Mills, 2002a; Griffin and Mills, 2002b; Mills and Griffin, 2000), although this appears to depend on the support provided by the seating (Mills and Griffin, 2000).

Given the similarity in the estimates for fore-aft and lateral motion weightings, it might tentatively be assumed that the frequency dependence of motion sickness caused by lateral and fore-aft oscillation are similar and may be reflected in the same acceleration frequency weighting.

Vertical oscillation

The present study shows that the frequency-dependence of motion sickness caused by lateral oscillation at frequencies less than 0.125 Hz may not be well represented by the frequency weighting, W_f, currently used for vertical oscillation (respectively having a slope of -12 dB/octave and a slope of +6 dB/octave above and below the corner frequencies at 0.25 Hz and 0.125). The difference between the two weightings at frequencies less than 0.125 Hz may reflect differences in the mechanisms causing sickness in the two axes but it may also reflect the limited knowledge of response to vertical oscillation at these low frequencies. It may also arise from the different degrees of sickness employed: 'mild nausea' in the present studies with lateral oscillation and vomiting in the studies with vertical oscillation.

6.6 CONCLUSIONS

For 0.0315 to 0.2 Hz lateral oscillations having the same peak velocity, the probability of mild nausea increases with increasing frequency of oscillation. Combining the present results with previous findings suggests that this degree of motion sickness may be predicted by an acceleration frequency weighting that is independent of frequency from 0.0315 to 0.25 Hz and reduces at 6 dB/octave (i.e. proportional to velocity) in the range 0.25 to 0.8 Hz. The suggested frequency-dependence for motion sickness caused by lateral oscillation may differ from that currently assumed for vertical oscillation, although the differences have not been tested statistically.

CHAPTER 7 EFFECT OF FREQUENCY WITH ROLL-COMPENSATED LATERAL OSCILLATION

7.1 INTRODUCTION

Laboratory studies of motion sickness found that combined lateral and roll oscillation tends to increase motion sickness compared with that caused by Earth-horizontal lateral oscillation alone (e.g. Förstberg, 1999). In addition, studies of motion sickness on tilting-trains indicated that motion sickness tended to increase with increasing roll-compensation (e.g. Förstberg *et al.*, 1998).

In tilting-trains, the discomfort associated with the Earth-horizontal lateral forces, arising from centrifugal forces as the train rounds a curve, are reduced by adding roll motion with an appropriate relative phase and magnitude: Figure 7.1 shows the special case where a seated-person is tilted so as to align the vertical axis of the body with the resultant force arising from gravity and centrifugal acceleration (i.e. the gravito-inertial force). In this case there is no apparent force in the subject's *y*-axis, although the apparent force in the subject's *z*-axis is increased. If the magnitude of the Earth-lateral force arising from inertial acceleration is small relative to the force due to gravity then the tilt-induced increase in vertical force will be small relative to the reduction in lateral force.

The aim of this study was to investigate the influence on motion sickness of lateral oscillation at frequencies in the range from 0.05 to 0.8 Hz, when lateral accelerations were fully compensated (i.e. 100% compensation) by roll motion.

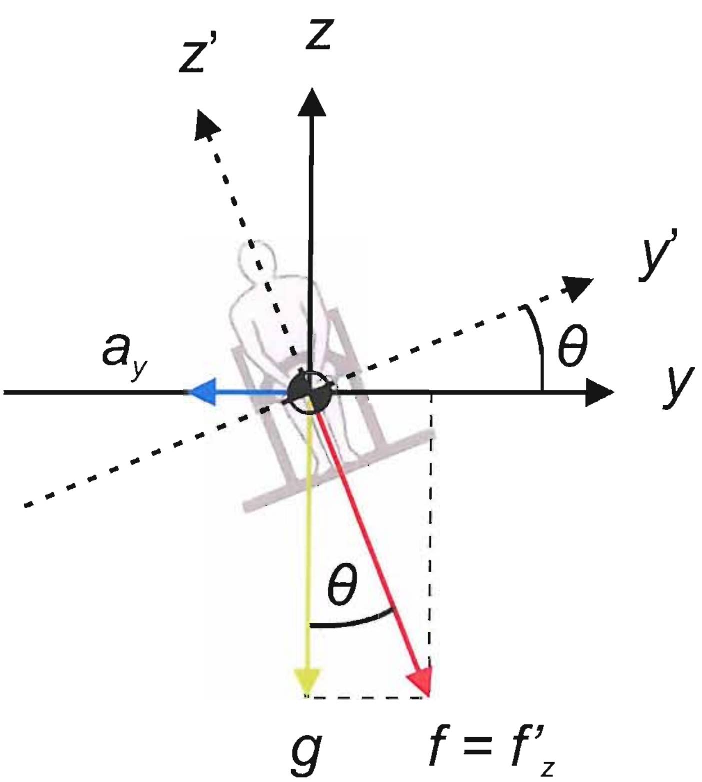

Figure 7.1 Force vector diagram for a seated subject undergoing 100% roll-compensated lateral oscillation with the centre of roll at the centre of the supporting seat surface. The resultant force, *f*, is the sum of the force due to inertial acceleration, given by a_y, and the gravity force, *g* (-9.81 m/s²), such that $f = g - a$. The subject z-axis is aligned with the resultant force and the required roll displacement of the subject reference frame relative to the Earth-reference frame, θ, is given by $\arctan(a_y/g)$. A prime is used to distinguish the subject reference frame (y', z') from the Earth-reference frame (y, z).

The previous study of lateral oscillation without roll motion (Chapter 6), suggested that motion sickness was dependent on acceleration with oscillations in the range from 0.05 to 0.25 Hz and dependent on velocity with oscillations in the range from 0.25 Hz to 0.8 Hz. As the lateral oscillation magnitudes in this experiment are equivalent to those studied in the previous experiment, it follows that two hypothesis are required: i) motion sickness is proportional to the oscillation frequency for lateral oscillations of constant peak velocity in the frequency range from 0.05 to 0.2 Hz, and ii) motion sickness is inversely proportional to the square of the frequency for lateral oscillations of constant peak jerk in the frequency range from 0.315 to 0.8 Hz. As in this study, the reports of motion sickness with fully (100%) roll-compensated lateral oscillation are compared to those reported in the conditions without roll motion, as studied in the previous chapter, then a third hypothesis is required and states: there is no difference in the motion sickness reported by subjects exposed to either uncompensated or 100% roll-compensated lateral oscillations.

7.2 MOTIONS

This study used sinusoidal Earth-horizontal lateral oscillations with frequencies in the range from 0.05 to 0.8 Hz and 100% roll compensation. The magnitudes of the Earth-lateral motions were equivalent to those used in the previous experiment (Chapter 6) and the motion parameters for these conditions are reported in Table 7.1.

As a function of time, the roll displacements, $\varphi(t)$ degrees, required for 100% compensation of the Earth-lateral force, $f_y(t) = -a_y(t)$ m/s², are given by:

$$\varphi(t) = -\arctan\left(\frac{f_y(t)}{g}\right)$$

Where: g is the specific force due to gravity (-9.81 m/s²).

Table 7.1 Roll-compensated lateral oscillation motion parameters

Frequency	Peak Earth-lateral displacement	Peak Earth-lateral velocity	Peak Earth-lateral acceleration	Relative phase of Earth-lateral and roll displacements	Peak roll displacement	Resultant peak lateral acceleration at seat surface
(Hz)	(m)	(ms^{-1})	(ms^{-2})	Radians	(°)	(ms^{-2})
0.05	3.18	1.0	0.31	0	1.83	0.00
0.08	1.99	1.0	0.50	0	2.93	0.00
0.125	1.27	1.0	0.79	0	4.58	0.00
0.16	0.99	1.0	1.01	0	5.85	0.00
0.20	0.80	1.0	1.26	0	7.30	0.00
0.315	0.25	0.5	0.99	0	5.76	0.00
0.5	0.06	0.2	0.63	0	3.67	0.00
0.8	0.02	0.0775	0.39	0	2.27	0.00

With these conditions and sinusoidal oscillation, the Earth-lateral displacements and roll displacements were in phase. The centre of roll was at the centre of the supporting seat surface so that a subject would not experience lateral acceleration at this location (i.e. at the ischial tuberosities).

7.3 RESULTS

7.3.1 Effect of oscillation frequency with 100% compensation

Matching subjects

Using the Kruskal-Wallis test, the eight independent groups of subjects exposed to 100% roll-compensated lateral oscillation were matched to each other for the six measures of self-rated motion sickness susceptibility: illness susceptibility in transport in the last year, $I_{susc(yr)}$ (χ^2 = 2.279, p = 0.943); vomiting susceptibility in the last year, $V_{susc(yr)}$ (χ^2 = 3.271, p = 0.859); total susceptibility to vomiting, V_{total} (χ^2 = 3.988, p = 0.781); total susceptibility to motion sickness, M_{total} (χ^2 = 5.005, p = 0.659); total susceptibility to motion sickness on land transport, M_{land} (χ^2 = 4.841, p = 0.679); and total susceptibility to motion sickness on non-land transport, $M_{non\text{-}land}$ (χ^2 = 6.491, p = 0.484).

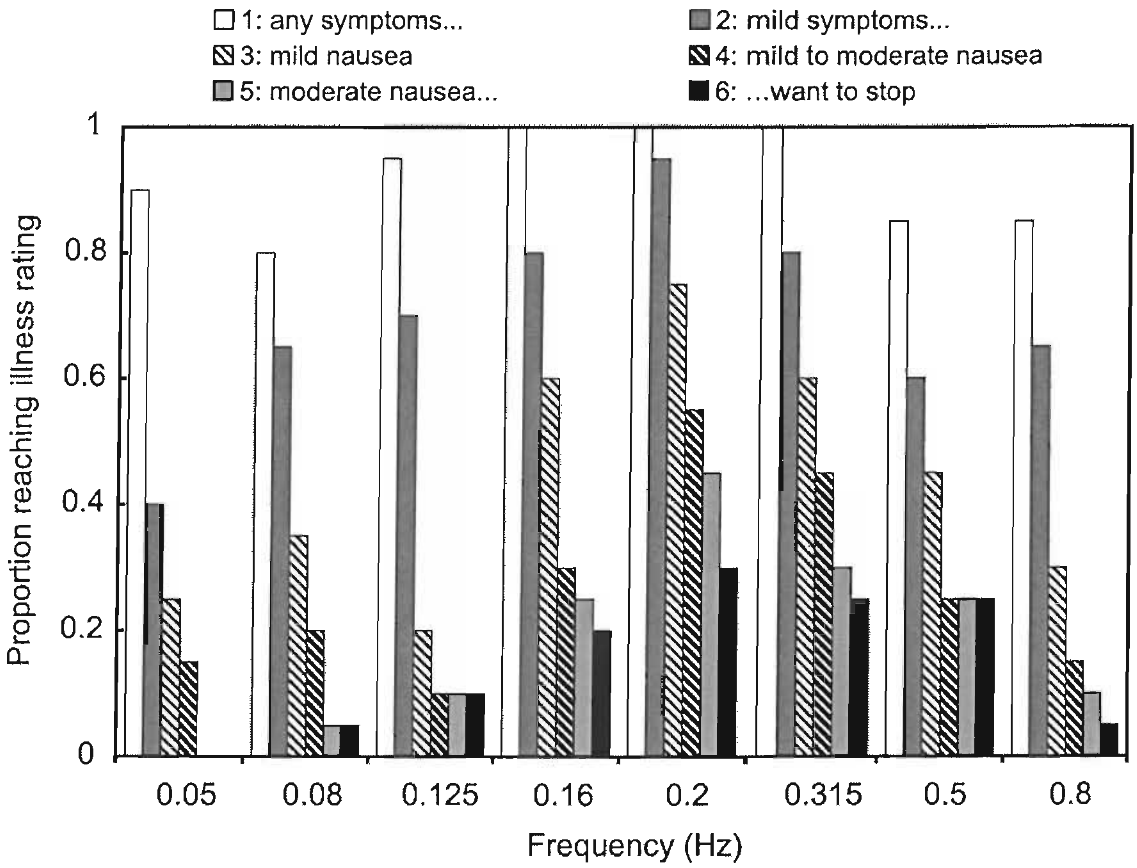

Figure 7.2 Proportion of subjects to reach each illness rating (1 to 6) at each frequency of oscillation with 100% roll-compensated lateral oscillation.

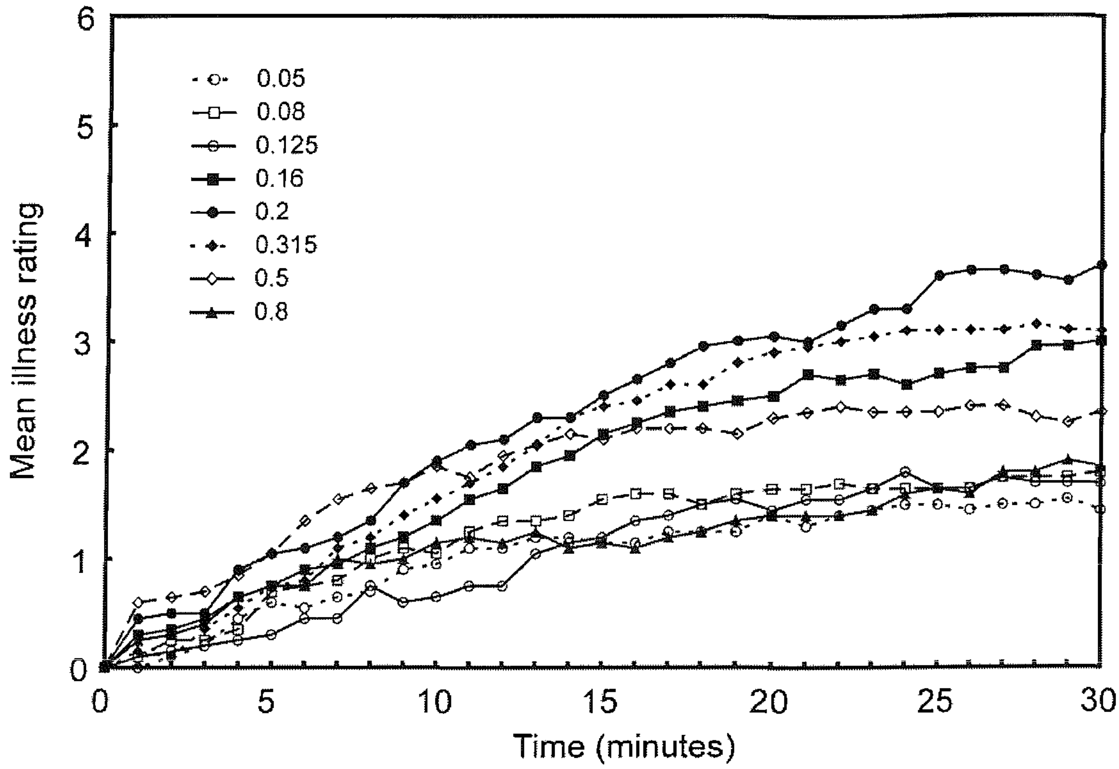

Figure 7.3 Mean illness ratings reported by the subjects at each minute of exposure for each frequency of 100% roll-compensated lateral oscillation.

Illness ratings

Over all conditions, 8.1% (13/160) of the subjects did not report any symptoms at any time during motion exposure (i.e. they reported only “0: no symptoms”), whilst 15.0% (24/160) of the subjects reported an illness rating of 6. With increasing oscillation frequency, Figure 7.2 shows that the proportion of subjects reaching each illness rating increased in the range from 0.05 to 0.2 Hz and then decreased in the range from 0.315 to 0.8 Hz. The mean illness ratings obtained from the 20 subjects in each condition tended to increase through the 30-minute exposures (Figure 7.3).

The median average illness ratings were calculated for each subject. The median average illness ratings were found for each condition and are shown in Figure 7.4. Over the eight frequencies of oscillation there were statistically significant differences in the average illness ratings (Kruskal-Wallis: $\chi^2 = 17.375$, $p = 0.015$).

Paired comparisons of conditions revealed that average illness ratings reported by subjects increased significantly with increasing oscillation frequency in the range from 0.05 to 0.2 Hz (Mann-Whitney U test: $p < 0.05$ between 0.08 and 0.2 Hz, 0.125 and 0.16 Hz; $p < 0.01$ between 0.05 and 0.2 Hz, 0.125 and 0.2 Hz).

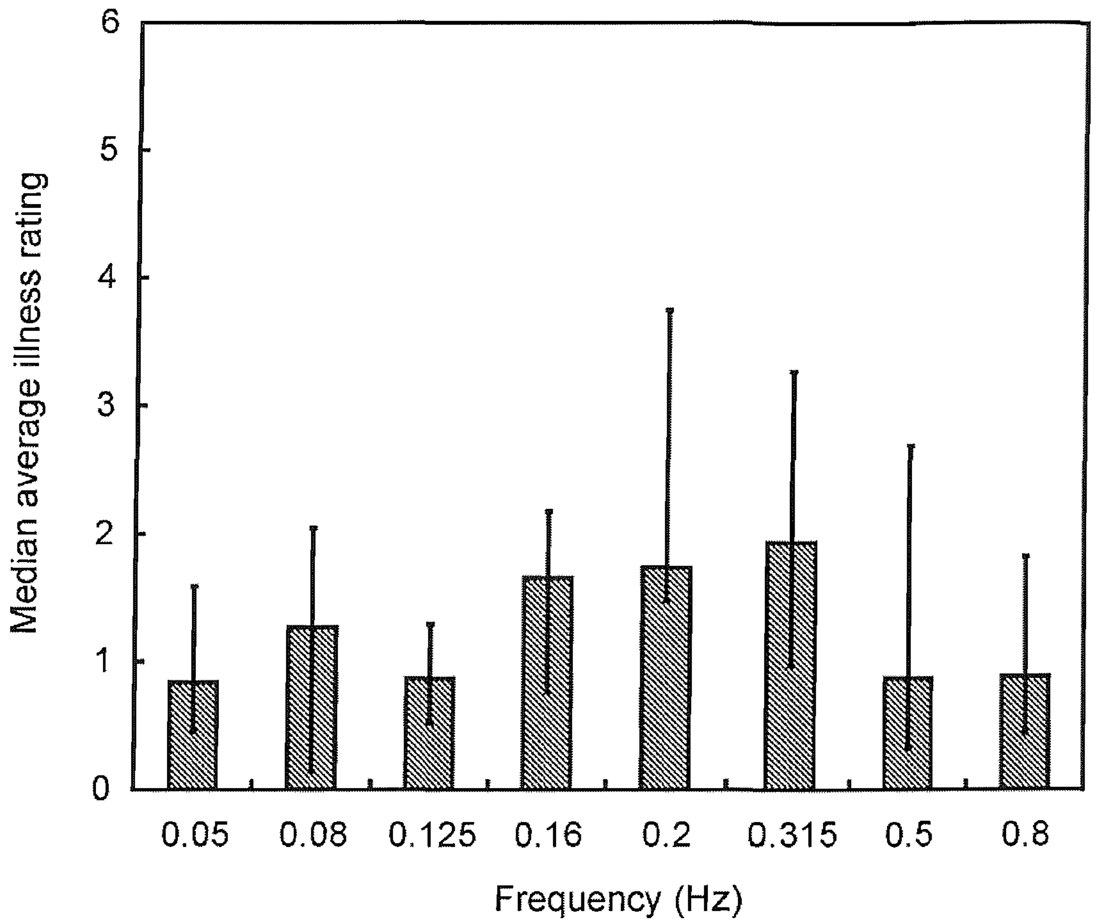

Figure 7.4 Median average illness ratings reported by the subjects with 100% roll compensated lateral motion for each frequency of oscillation. Upper and lower error bars indicate the 25th and 75th percentile average illness ratings respectively.

With oscillations in the frequency range from 0.315 to 0.8 Hz, average illness ratings decreased significantly with increasing frequency (Mann-Whitney U test: $p < 0.05$ between 0.315 and 0.8 Hz).

7.3.2 Motion sickness with 0% and 100% compensation

Method

The reports of motion sickness caused by 100% roll-compensated lateral oscillation at one of eight frequencies of roll-compensated lateral oscillation were compared to those caused by uncompensated lateral oscillation at one of eight frequencies reported in the previous chapter (0.05, 0.08, 0.125, 0.16, 0.2, 0.315, 0.5 and 0.8 Hz).

Matching subjects

The subjects for this experiment were selected so that they had similar motion sickness susceptibilities to the subjects who participated in the experiment reported in Chapter 7. Statistical analysis (Kruskal-Wallis tests) confirmed that the 16 independent groups did not differ from each other for the six measures of self-rated motion sickness susceptibility:

illness susceptibility in transport in the last year, $I_{susc(yr)}$ (χ^2 = 20.688, p = 0.147); vomiting susceptibility in the last year, $V_{susc(yr)}$ (χ^2 = 12.123, p = 0.670); total susceptibility to vomiting, V_{total} (χ^2 = 13.877, p = 0.535); total susceptibility to motion sickness, M_{total} (χ^2 = 9.740, p = 0.836); total susceptibility to motion sickness on land transport, M_{land} (χ^2 = 9.755, p = 0.835); and total susceptibility to motion sickness on non-land transport, $M_{non\text{-}land}$ (χ^2 = 15.218, p = 0.436).

Comparison of illness ratings

Figure 7.5 shows the median average illness ratings for each frequency of uncompensated and 100% roll-compensated lateral oscillation. At all frequencies of oscillation other than 0.125 and 0.8 Hz, 100% roll-compensation caused higher median average illness ratings than uncompensated oscillation. For each of the eight frequencies of oscillation, average illness ratings were compared between the uncompensated and compensated lateral oscillation conditions. The comparisons revealed a highly significant difference (Mann-Whitney U test: $p < 0.01$) with oscillation at 0.315 Hz.

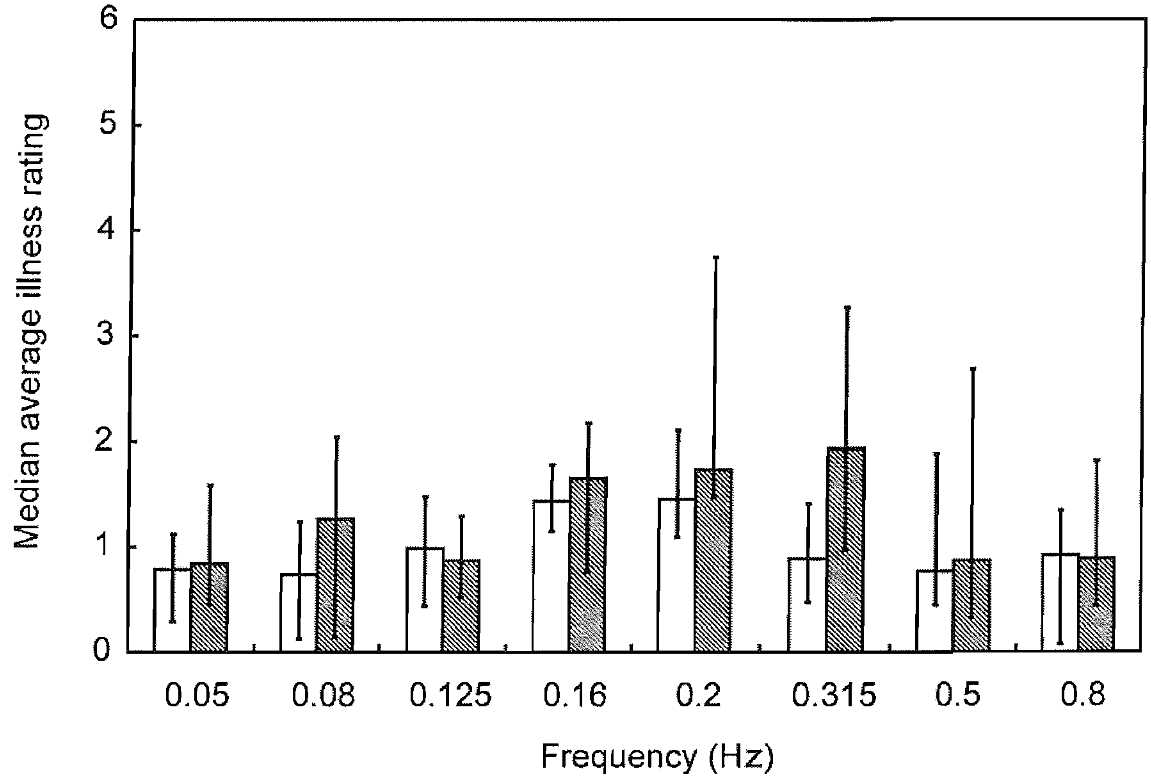

Figure 7.5 Median average illness ratings reported by the subjects with 0% compensation (white bars) and 100% compensation (shaded bars) at each frequency of oscillation. Upper and lower error bars indicate the 25th and 75th percentile average illness ratings respectively.

7.4 COX REGRESSION ANALYSIS

7.4.1 Dependent and independent variables

Cox regression analysis was used to relate the exposure duration required to report a given illness rating to the frequency of oscillation, the compensation (whether roll compensation was present or not) and the self-reported motion sickness susceptibility. Four separate analyses were performed, one for each of four illness ratings: "1 – Any symptoms, however slight"; "2 – Mild symptoms, e.g. stomach awareness, but not nausea"; "3 – Mild nausea"; and "4 – Mild to moderate nausea".

The variables frequency, compensation, age, $I_{susc(yr)}$, $V_{susc(yr)}$, V_{total}, $\log_{10}(M_{total}+3)$, $\log_{10}(M_{land}+3)$ and $\log_{10}(M_{non\text{-}land}+3)$ were considered for entry into the Cox regression model. The categorical variable frequency*compensation was also considered for entry, so as to test for interactions between frequency and compensation.

To avoid entering two or more correlated motion sickness susceptibility variables into the same model, for each illness rating of interest, separate regression models were formed for each susceptibility measure. The procedure required two analysis blocks to each model: in the first block, a single motion sickness susceptibility measure was entered into the model using the entry method; in the second block, a forward selection algorithm, based on the likelihood ratio statistic, was used to select one or more of the motion variables (frequency, compensation and their interaction term). For each illness rating, the model with the best overall fit (based on the chi-square statistic) was selected.

In order to improve their distribution, the variables M_{total}, M_{land} and $M_{non\text{-}land}$ were logarithm (base 10) transformed prior to analysis (a constant of 3 was first added to avoid taking the logarithm of negative or zero values). The following variables were transformed to categorical variables prior to being entered into the Cox regression analysis[12]: compensation, frequency, $I_{susc(yr)}$ (4 categories: 0, $0 < I_{susc(yr)} \leq 0.120$, $0.120 < I_{susc(yr)} \leq 0.683$, $0.683 < I_{susc(yr)} \leq 1.67$), $V_{susc(yr)}$ (3 categories: 0, $0 < V_{susc(yr)} \leq 0.167$, $0.167 < V_{susc(yr)} \leq 1.67$), and V_{total} (4 categories: 0, 1, $2 \leq V_{total} \leq 6$, 7). The reference categories for the categorical variables entered into the models were 0.05 Hz for frequency, 0% for compensation, and 0 for $I_{susc(yr)}$, $V_{susc(yr)}$ and V_{total}.

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[12] Prior to transformation into categorical variables, the $I_{susc(yr)}$, $V_{susc(yr)}$, and V_{total} categories were determined using the 'visual bander' function supplied in the SPSS statistical software package (SPSS; version 12.0, SPSS, Chicago, IL). The cut-points between categories were selected automatically to be the 25th, 50th and 75th percentiles. To form variable categories that would be consistent across all investigations, the categorical variable transformation was applied to all 23 conditions reported in this thesis.

7.4.2 Results

Table 7.2 gives the exponents of the regression coefficients and statistical significance for the variables remaining in each of the Cox regression models. All analyses discarded the variables age, $V_{susc(yr)}$, V_{total}, $\log_{10}(M_{non\text{-}land}+3)$ and compensation from the model. These motion and motion sickness susceptibility variables did not significantly improve the predictive properties of the models.

Table 7.2 Results of the Cox regression models.

Illness rating of interest:	"1 – any symptoms…"		"2 – mild symptoms…"		"3 – mild nausea"		"4 – mild to moderate nausea"	
Overall:	$\chi^2 = 53.160$, $P < 0.01$**		$\chi^2 = 60.351$, $p < 0.01$**		$\chi^2 = 69.879$, $p < 0.01$**		$\chi^2 = 64.661$, $p < 0.01$**	
Variable	Exp(ß)	p	Exp(ß)	p	Exp(ß)	p	Exp(ß)	p
$\text{Log}_{10}(M_{total}+3)$	2.931	< 0.01**	3.457	< 0.01**	---	---	---	---
Group $I_{susc(yr)}$	---	---	---	---	---	< 0.01**	---	< 0.01**
$I_{susc(yr)}$ (1)	---	---	---	---	1.055	0.842	0.280	0.037*
$I_{susc(yr)}$ (2)	---	---	---	---	2.057	< 0.01**	2.313	< 0.01**
$I_{susc(yr)}$ (3)	---	---	---	---	0.000	0.969	0.000	0.975
Frequency:	---	< 0.01**	---	< 0.01**	---	0.023*	---	---
0.08 Hz	0.815	0.396	1.399	0.279	0.869	0.838	---	---
0.125 Hz	1.124	0.622	1.513	0.174	1.838	0.274	---	---
0.16 Hz	1.371	0.178	2.740	< 0.01**	2.575	0.063†	---	---
0.2 Hz	1.824	< 0.01**	3.044	< 0.01**	3.949	< 0.01**	---	---
0.315 Hz	1.426	0.128	2.059	0.016*	1.294	0.682	---	---
0.5 Hz	0.974	0.913	1.575	0.143	2.489	0.088†	---	---
0.8 Hz	0.761	0.262	1.380	0.299	0.562	0.473	---	---
Comp * Freq:	---	---	---	---	---	0.039*	---	< 0.01**
C*F (0.08 Hz)	---	---	---	---	2.621	0.164	1.577	0.406
C*F (0.125 Hz)	---	---	---	---	0.540	0.341	0.802	0.766
C*F (0.16 Hz)	---	---	---	---	1.780	0.199	2.970	0.020*
C*F (0.2 Hz)	---	---	---	---	1.594	0.241	5.894	< 0.01**
C*F (0.315 Hz)	---	---	---	---	3.707	0.024*	4.401	< 0.01**
C*F (0.5 Hz)	---	---	---	---	1.429	0.481	2.333	0.092†
C*F (0.8 Hz)	---	---	---	---	3.035	0.174	1.283	0.687

The variables frequency, compensation and $I_{susc(yr)}$ were entered as categorical variables in the analysis with 0.05 Hz oscillation, 0% compensation and $I_{susc(yr)} = 0$ as the reference conditions respectively. † = $p < 0.1$; * = $p < 0.05$; ** = $p < 0.01$.

The occurrences of each of the illness ratings were better predicted by models including a covariate based on the subjects' reported motion sickness susceptibilities. The logarithm-transformed total susceptibility to motion sickness, $\log_{10}(M_{total}+3)$, highly significantly (p < 0.01) influenced the occurrence of the lowest two illness ratings (i.e. "1 – any symptoms..." and "2 – mild symptoms..."), whilst the categorically recoded illness susceptibility in the previous year, $I_{susc(yr)}$, highly significantly influenced ($p < 0.01$) the occurrence of the two illness ratings specifically relating to nausea (i.e. "3 – Mild nausea" and "4 – Mild to moderate nausea").

Oscillation frequency was found to have a significant effect upon the risks of subjects reporting illness ratings 1 to 3 (1: $p < 0.01$; 2: $p < 0.01$; 3: $p < 0.05$). Relative to the illness ratings reported with oscillations at 0.05 Hz, the risks of reporting each illness rating increased significantly with increasing frequency up to 0.2 Hz, whereas the risks decreased with increasing frequency above 0.2 Hz. For example, subjects exposed to oscillation at 0.2 Hz were approximately four times more likely to report "3 - Mild nausea" than subjects exposed to oscillation at 0.05 Hz and approximately eight times more likely to report "3 - Mild nausea" than subjects exposed to oscillation at 0.8 Hz. The variable frequency did not improve predictions of reports of "4 – Mild to moderate nausea".

A significant interaction occurred between frequency and compensation such that the cross-term, frequency*compensation, had a significant overall influence on the occurrence of illness ratings "3" ($p < 0.05$) and "4" ($p < 0.01$). Compared to the influence of compensation with oscillation at 0.05 Hz, the effect of 100% roll-compensation on the risk of reaching "3: Mild nausea" was only significant with frequencies of oscillation at 0.315 Hz ($p < 0.05$); the relative risk was 3.707. Although not always statistically significant, relative to oscillation at 0.05 Hz, the risks associated with the frequency*compensation interaction were greater at all test frequencies, except 0.125 Hz, indicating that compensation tended to increase the chances of motion sickness. Similar findings were obtained with the model for "4: mild to moderate nausea" where the effect of the frequency*compensation interaction was significant with oscillation at 0.16 ($p < 0.05$), 0.2 ($p < 0.01$) and 0.315 Hz ($p < 0.01$). The relative risk of reaching "4" was greatest at 0.2 Hz (5.894) with the risk increasing with increasing frequency in the frequency range below 0.2 Hz and decreasing with increasing frequency in the frequency range above 0.2 Hz.

7.5 DISCUSSION

7.5.1 Introduction

With various frequencies and magnitudes of oscillation, systematic and significant differences in motion sickness were observed between uncompensated and 100% roll-compensated lateral oscillation. The discussion aims to identify how motion sickness varies with changes in oscillation frequency and roll-compensation.

7.5.2 Effect of frequency on motion sickness with 100% compensation

With the same magnitudes of lateral oscillation, comparisons of the average illness ratings suggest that motion sickness caused by 100% roll-compensated lateral oscillation had a similar dependence on the frequency of oscillation as that found with uncompensated lateral oscillations in the previous experiment (Chapter 6): with 100% roll-compensated lateral oscillations having the same peak velocity (±1.0 m/s) in the frequency range from 0.05 to 0.2 Hz, average illness ratings increased with increasing oscillation frequency; whereas, with 100% roll-compensated lateral oscillations having the same peak jerk (±1.96 m/s^3) at frequencies in the range from 0.315 to 0.8 Hz, the average illness ratings decreased with increasing oscillation frequency. Similar findings were obtained from Cox regression analysis, which found significant overall effects of frequency on the risks of subjects reporting illness ratings "1 – Any symptoms..." to "3 – mild nausea".

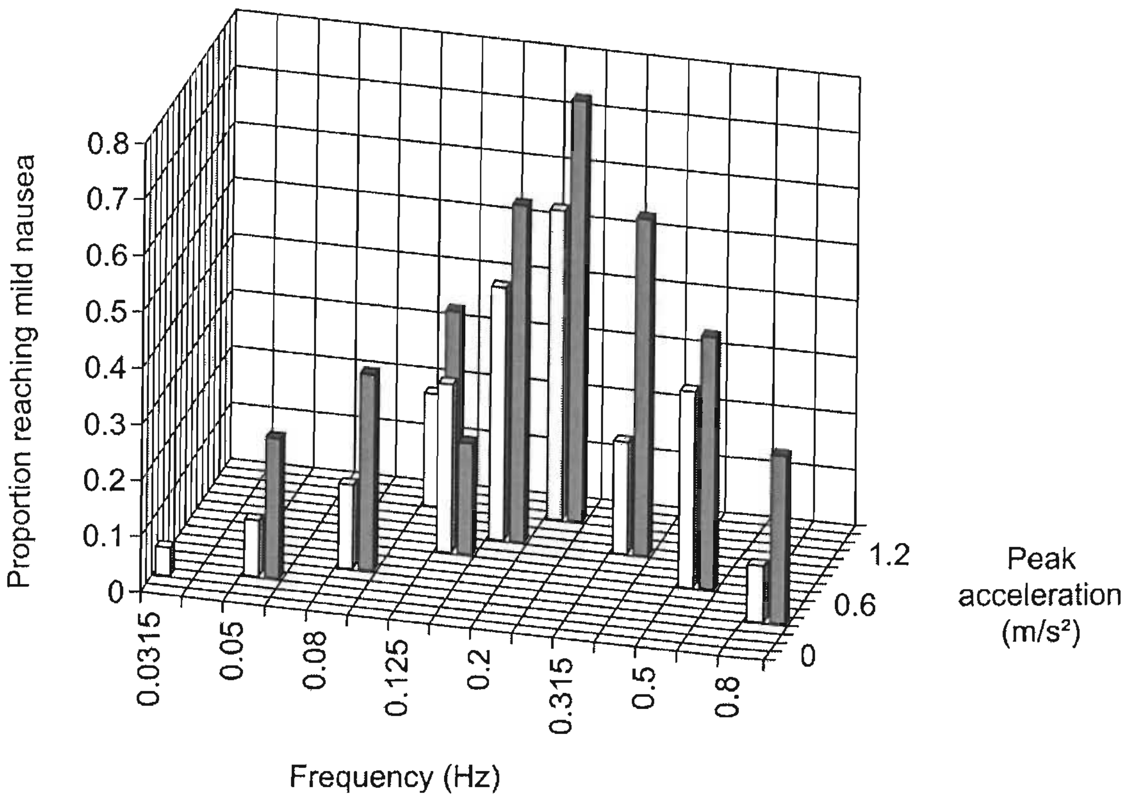

Figure 7.6 Summary of the proportion of subjects reporting mild nausea at each magnitude and frequency of uncompensated and 100% roll-compensated lateral oscillation.

With the 100% roll-compensated motions employed in the study, as the oscillation frequency increased from 0.05 Hz to 0.2 Hz, the Earth-lateral accelerations and the roll displacements increased. Similarly, as the oscillation frequency increased in the range from 0.315 to 0.8 Hz, the Earth-lateral accelerations and the roll displacements decreased. With only one magnitude of motion at each frequency, it is not obvious whether the changes in motion sickness were due to progressive changes in frequency, acceleration, or roll angle.

7.5.3 Comparison of 0% and 100% compensation

Inspection of the median average illness ratings (Figure 7.5) and the proportions of subjects reporting "3 – mild nausea" (Figure 7.6) at each oscillation frequency suggest that 100% compensated lateral oscillation tends to cause more motion sickness than uncompensated lateral oscillation: Figure 7.6 shows the proportion of subjects reporting "3 – Mild nausea" at each frequency and magnitude of uncompensated and 100% roll-compensated lateral oscillation (including data with oscillations at 0.1 Hz from Chapter 8). At all oscillation frequencies other than at 0.125 Hz, the proportions of subjects reporting "3 – Mild nausea" were greater with 100% roll-compensated lateral oscillation than with uncompensated lateral oscillation. Paired statistical comparisons of the average illness ratings with uncompensated and fully roll-compensated lateral oscillations revealed a significant difference only at 0.315 Hz. It may be that only one statistical difference was found if there was an insufficient statistical power relative to the size of the differences that were observed. In contrast Cox regression modelling found a significant overall effect of the interaction of frequency and compensation when modelling the time to reach "3 – Mild nausea" or "4 mild to moderate nausea", such that a compensation term significantly improved the model. At all oscillation frequencies other than 0.125 Hz, the relative risk associated with adding roll compensation was greater than 1.0 indicating that the risk of motion sickness was increased. A finding of significantly more motion sickness with 100% roll-compensation than with uncompensated lateral oscillation would be consistent with previous observations using different motion waveforms (Förstberg, 1999).

It is unclear whether or not the effect of compensation is dependent on the frequency of oscillation. When Cox regression was used to model reports of "3 – Mild nausea" with both uncompensated and 100% roll-compensated lateral oscillations, significant effects of the oscillation frequency and a significant interaction between the frequency of oscillation and compensation were found but there was no significant overall effect of compensation. These findings indicate that the reports of "3 – Mild nausea" were modelled better when the effect of compensation was allowed to vary with frequency, which in this analysis meant that it varied for each condition; however, with this model, the relative risks did not follow any systematic dependence on frequency. Cox regression modelling of reports of "4

– Mild to moderate nausea" also predicted a significant interaction between compensation and frequency. With this model, the risks did appear to change systematically with frequency; however, there was no overall effect of the variables frequency or compensation. With uncompensated lateral oscillations, there were insufficient reports of "4 – Mild to moderate nausea" for the Cox regression models to converge (Chapter 6). It is suggested that the changes in the risks associated with the interaction between frequency and compensation may reflect an overall effect of frequency, which became apparent when the levels of nausea were increased by roll-compensation of the lateral oscillations.

7.5.4 Frequency weightings for combined lateral and roll oscillations

Previous studies have employed acceleration frequency weightings to represent the effects of oscillation magnitude and oscillation frequency on motion sickness and a weighting has been successfully applied to predict motion sickness caused by vertical oscillation on ships. For the special case of 100% compensated lateral oscillation, a frequency weighting may be of limited practical value as the environments in which these motions exist are rare. However, when compared to that for pure lateral oscillation, a frequency weighting for 100% compensation might illustrate the relative influences of lateral and roll oscillation on motion sickness with combined lateral and roll oscillation.

It is likely that motion sickness caused by combined lateral and roll oscillation cannot be predicted from a single independent variable. Collective findings from studies of pure roll oscillation (e.g. Howarth and Griffin, 2003), pure lateral oscillation (Chapter 6) and this investigation of 100% roll-compensated lateral oscillation, indicate that motion sickness is unlikely to be predicted from only one of the three variables: subject-lateral force, roll displacement, or Earth-lateral force. With pure roll oscillation and subject-lateral forces similar to those studied in the previous experiment (Chapter 6), relative to a stationary condition subjects did not always report significant motion sickness (Howarth and Griffin, 2003). With pure lateral oscillation (no roll) and subject-lateral forces similar to those in the study of roll oscillation (Howarth and Griffin, 2003), relative to a stationary condition subjects reported significant sickness (Chapter 6). With subjects feeling no lateral forces but similar magnitudes of roll to those used in the study of roll (Howarth and Griffin, 2003), subjects reported the greatest motion sickness.

It is suggested that an 'Earth-lateral acceleration frequency-weighting' is used to compare the relative effects of oscillation frequency and magnitude with uncompensated lateral oscillations and with 100% roll-compensated lateral oscillations. With 100% roll-compensated lateral oscillations, subjects do not feel any subject-lateral acceleration while with Earth-horizontal lateral oscillations there are no roll motions. Thus, the use of either a 'subject-lateral acceleration frequency weighting' or a 'roll displacement frequency weighting' would be unsuitable – as the former would predict 'infinite' sensitivity to motion sickness with 100% roll-compensated oscillations (since there is sickness but no lateral acceleration), whereas the latter would predict infinite sensitivity to motion sickness with Earth-horizontal lateral oscillations (since there is sickness but no roll displacement).

An Earth-horizontal acceleration frequency-weighting for each frequency of 100% roll-compensated lateral oscillation was formed by normalising the proportion of subjects reporting "3 – Mild nausea" by the root-mean-square Earth-lateral acceleration magnitude. In Figure 7.7, the weightings are compared with the form of the lateral acceleration frequency-weighting suggested in the previous chapter. For convenience, the lateral acceleration frequency-weighting was normalised to be equal to 1.0 at frequencies less than 0.25 Hz.

With frequencies of oscillation up to 0.315 Hz, a simple asymptotic approximation to the 100% roll-compensation weightings would suggest a form close to that for the Earth-lateral acceleration frequency-weighting, suggesting that roll-compensated lateral oscillation has a similar dependence on oscillation frequency to uncompensated lateral oscillations in this frequency range; however, the weightings calculated with roll-compensated lateral oscillations at 0.1 and 0.125 Hz differ from an acceleration dependent acceleration frequency weighing. This may suggest that the effect of frequency is complex or the differences may be due to chance.

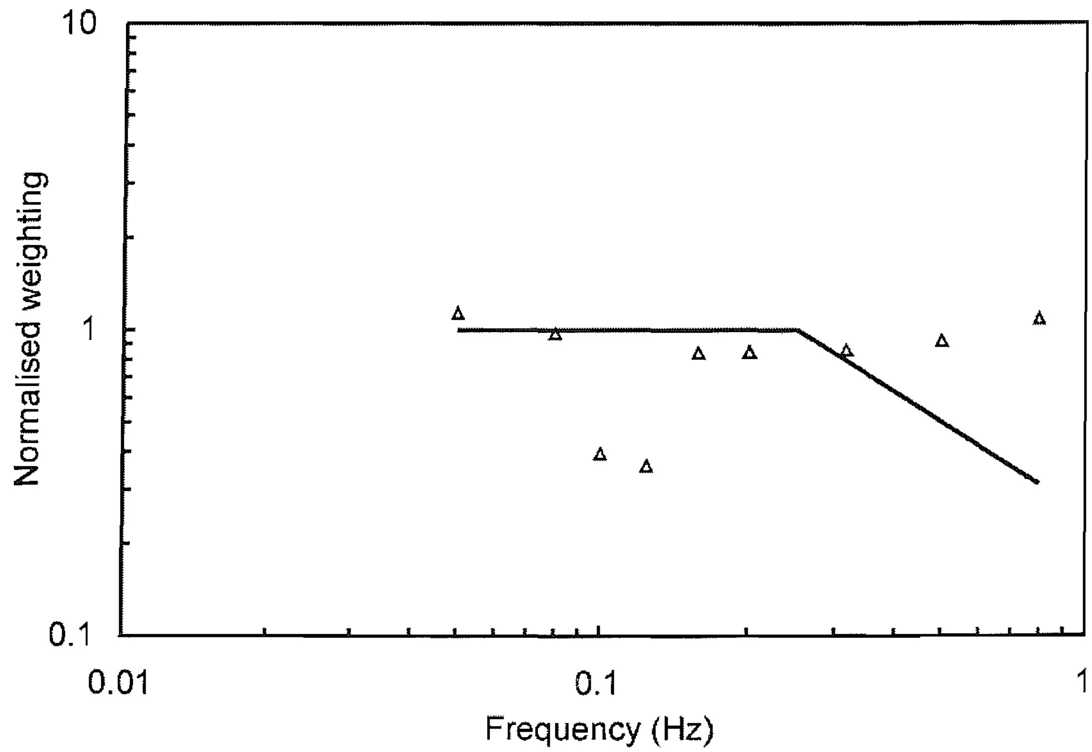

Figure 7.7 Proportion of subjects reporting "3 – Mild nausea" divided by the root-mean-square Earth-lateral acceleration at each frequency of 100% roll-compensated lateral oscillation (open triangles) and the asymptotic acceleration frequency weighting suggested for uncompensated lateral motions, but normalised to be equal to 1.0 at frequencies below 0.25 Hz (solid line).

With oscillation frequency increasing above 0.315 Hz, the weightings diverge, such that the 100% roll-compensated oscillation weightings suggest a weighting dependent on the Earth-lateral acceleration, whilst the asymptotic weighting for uncompensated lateral oscillation was dependent on Earth-lateral velocity. The differences may be accounted for by a previously discussed non-linear effect of acceleration magnitude (Chapter 6): the asymptotic frequency weighting for lateral acceleration was formed partially from data using different acceleration magnitudes to those studied here. If motion sickness does not increase linearly with increasing Earth-lateral acceleration then the two studies of the same lateral oscillation frequencies but different acceleration magnitudes will not predict similar weightings.

7.6 CONCLUSIONS

Reports of motion sickness with lateral and roll oscillation cannot be predicted from either the roll or lateral motion information alone. In conditions of lateral oscillation where roll is added to remove the lateral forces felt by subjects there will be significantly more motion sickness than if there were no roll motion added. With oscillations in the range from 0.05 to 0.315 Hz, the effect of lateral oscillation frequency on motion sickness with 100% roll-compensation is similar to that found with uncompensated lateral oscillations.

CHAPTER 8 EFFECT OF PERCENTAGE COMPENSATION

8.1 INTRODUCTION

Observations of motion sickness in the previous experiment could not be predicted from either the roll motion or the lateral motion alone. Instead some combination of the lateral and roll motion information must be used to predict motion sickness. This experiment aims to investigate how reports of motion sickness with lateral oscillation at two frequencies and the same peak acceleration magnitude change when the level of compensating roll motion is increased progressively so as to decrease progressively the lateral force felt by subjects. The previous experiment found that reports of motion sickness were greater with roll-compensated lateral oscillation than with uncompensated lateral oscillation, thus it is hypothesised that symptoms of motion sickness would increase with increasing compensation and that the effect would be independent of frequency.

8.2 MOTIONS

The experimental conditions were arranged in two parts: the first part investigated 0.2 Hz lateral oscillation with a peak acceleration magnitude equal to that studied with 0% and 100% compensation but with roll added to provide 50% compensation; the second part involved 5 conditions of 0.1 Hz lateral oscillation with the same peak acceleration magnitude as the 0.2 Hz lateral oscillation condition but 5 percentages of roll-compensation (0%, 25%, 50%, 75% and 100%). The motion characteristics for all the conditions compared in this investigation are summarised in Table 8.1.

Table 8.1 Roll-compensated lateral oscillation motion parameters.

Frequency	Compensation	Peak lateral displacement	Peak lateral acceleration	Peak roll displacement	Relative phase of lateral and roll displacements	Resultant peak acceleration at seat surface
(Hz)	(%)	(m)	(ms^{-2})	(°)	(radians)	(ms^{-2})
0.2	0	±0.80	±1.26	0	0	±1.26
0.2	50	±0.80	±1.26	±3.67	0	±0.63
0.2	100	±0.80	±1.26	±7.36	0	0
0.1	0	±3.18	±1.26	0	0	±1.26
0.1	25	±3.18	±1.26	±1.84	0	±0.95
0.1	50	±3.18	±1.26	±3.67	0	±0.63
0.1	75	±3.18	±1.26	±5.50	0	±0.32
0.1	100	±3.18	±1.26	±7.36	0	0

As a function of time, the roll displacement, $\varphi(t)$ degrees, producing the desired percentage of compensation, p, felt by subjects at the centre of roll, for a given Earth-lateral force, $f_y(t) = -a_y(t)$ m/s², was calculated from the expression below:

$$\varphi(t) = -\arctan\left(\frac{f_y(t)\cdot p}{g}\right)$$

Where: g is the specific force due to gravity (-9.81 m/s²). A proof of this relationship is offered in Appendix I.

Alternatively, the roll displacement, $\varphi(t)$, (in radians) may be approximated using

$$\varphi(t) \approx -\frac{f_y(t)\cdot p}{g}$$

8.3 RESULTS

8.3.1 Subjects

For each of the six measures of motion sickness susceptibility, the eight groups of subjects were matched to each other (using a Kruskal-Wallis test): illness susceptibility in transport in the last year, $I_{susc(yr)}$ (χ^2 = 3.985, p = 0.782); vomiting susceptibility in transport in the last year, $V_{susc(yr)}$ (χ^2 = 4.801, p = 0.684); total susceptibility to vomiting in transport, V_{total} (χ^2 = 7.924, p = 0.339); total susceptibility to motion sickness in transport M_{total} (χ^2 = 3.112, p = 0.874); total susceptibility to motion sickness on land transport M_{land} (χ^2 = 3.114, p = 0.874); and total susceptibility to motion sickness on non-land transport $M_{non\text{-}land}$ (χ^2 = 4.180, p = 0.759).

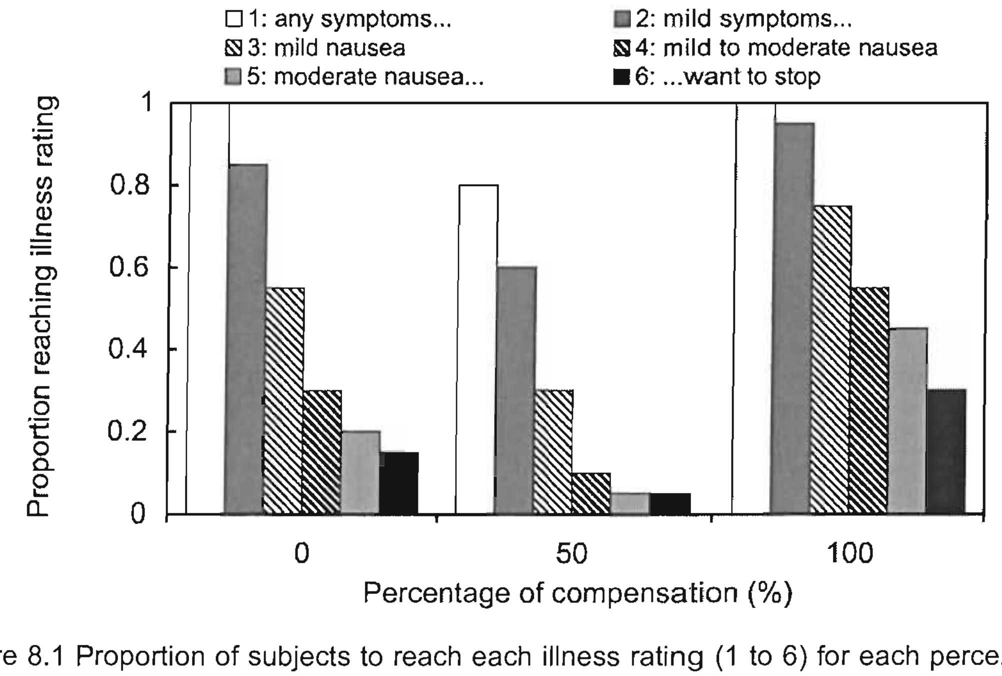

Figure 8.1 Proportion of subjects to reach each illness rating (1 to 6) for each percentage of roll compensation with lateral oscillation at 0.2 Hz.

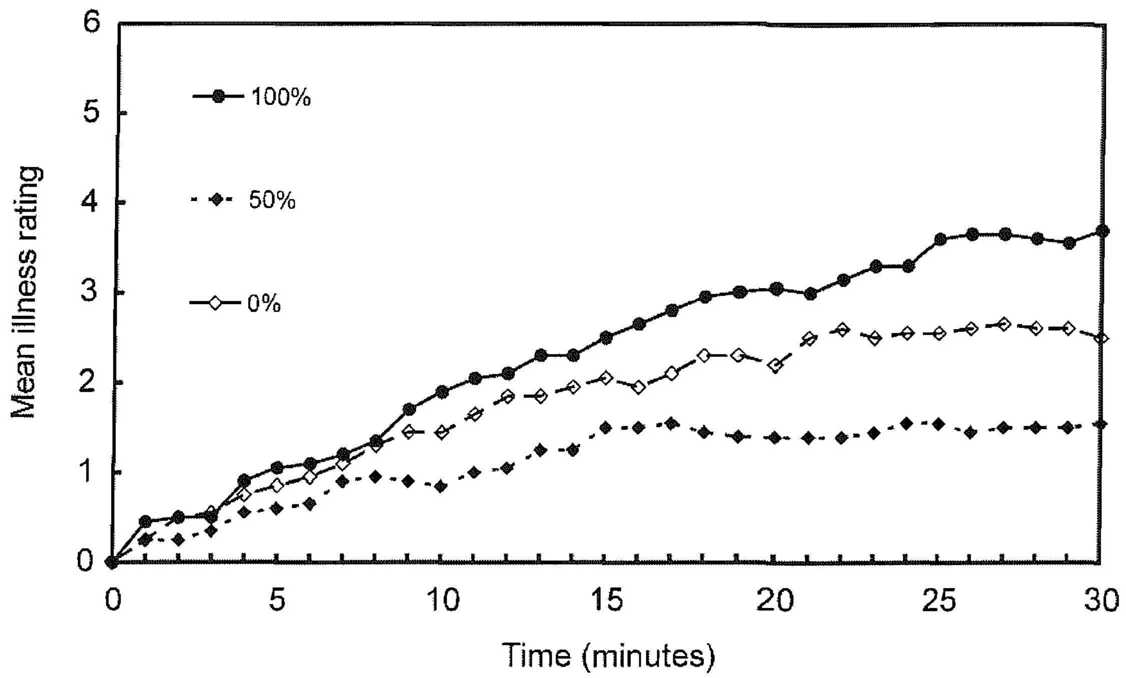

Figure 8.2 Mean illness ratings reported by the subjects at each minute of exposure for each percentage of roll-compensated lateral oscillation at 0.2 Hz and in a stationary condition.

8.3.2 <u>0.2 Hz lateral oscillation</u>

The proportions of subjects reaching each illness rating in each condition (0, 50 and 100%) of roll-compensated 0.2 Hz lateral oscillation are shown in Figure 8.1. Over the three compensation conditions, 7% (i.e. 4 out of 60 subjects) did not report any symptoms at any time during motion exposure (i.e. they reported "0: No symptoms" throughout), whilst 17% (i.e. 10 out of 60 subjects) reported an illness rating of 6.

The mean illness ratings obtained each minute from the 20 subjects in each of the three motion conditions tended to increase throughout the 30-minute exposures (Figure 8.2).

There were highly significant differences in the average illness ratings across the three motion conditions (Kruskal Wallis: $\chi^2 = 9.348$, $p < 0.01$). Further paired comparisons of the average illness ratings established that uncompensated lateral oscillation produced marginally more illness than 50% roll-compensation ($p < 0.1$), and 100% roll-compensation caused significantly more illness than 50% roll-compensation ($p < 0.01$).

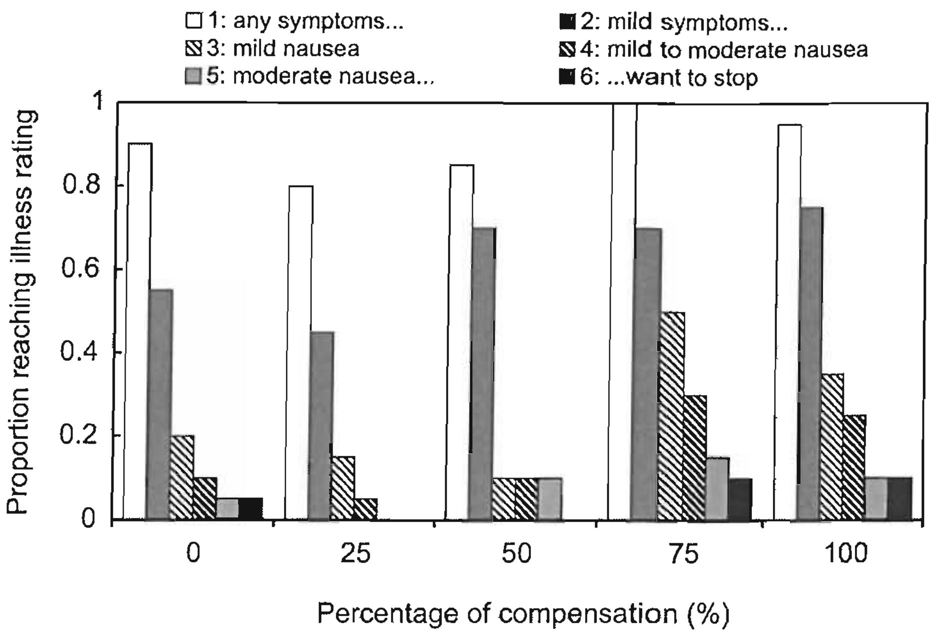

Figure 8.3 Proportion of subjects to reach each illness rating (1 to 6) for each percentage of roll compensation with lateral oscillation at 0.1 Hz.

8.3.3 <u>0.1 Hz lateral oscillation</u>

Over the five motion conditions, 10% (i.e. 10 out of 100 subjects) did not report any symptoms at any time during motion exposure (i.e. they reported "0: No symptoms" throughout), whilst 5% (i.e. 5 out of 100 subjects) reported an illness rating of 6. For each compensation condition, the proportions of subjects reaching each illness rating are shown in Figure 8.3. The mean illness ratings obtained each minute over 20 subjects for each of the five motion conditions tended to increase throughout the 30-minute exposures (Figure 8.4).

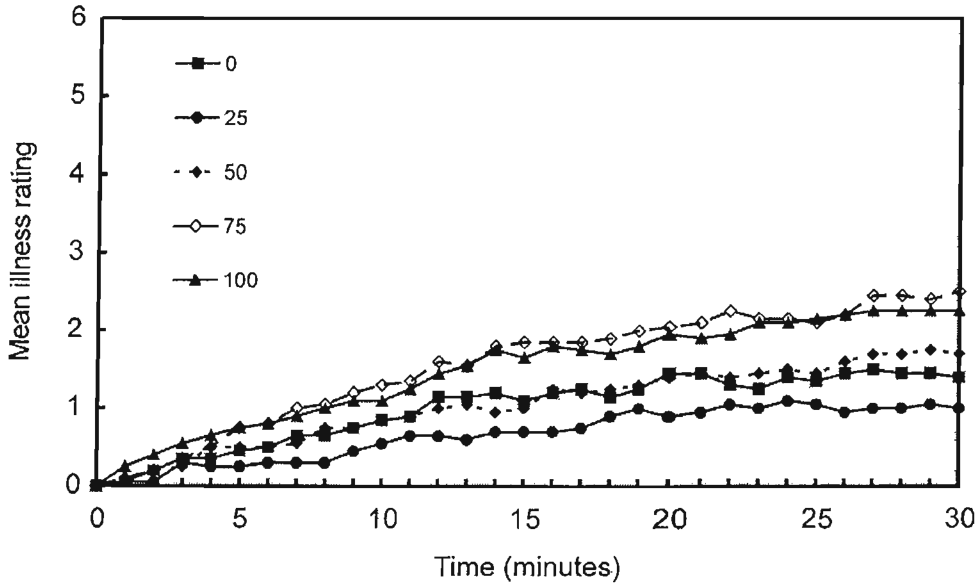

Figure 8.4 Mean illness ratings reported by the subjects at each minute of exposure for each percentage of roll-compensated lateral oscillation at 0.1 Hz.

There were marginally significant differences in the average illness ratings across the five motion conditions (χ^2 = 8.923, p = 0.063, Kruskal-Wallis). Paired comparisons of the average illness ratings in each of the five conditions revealed that the 25% roll-compensated lateral oscillation produced significantly less illness than 75% and 100% roll-compensation (p = 0.014 and p = 0.021 respectively). There were no statistical differences between other pairs of conditions.

8.4 COX REGRESSION ANALYSIS

Dependent and independent variables

Cox regression analysis was used to relate the exposure period required for a subject to report "3 – Mild nausea" to various measures of the subject and motion characteristics.

The variables percentage compensation, frequency, age, $I_{susc(yr)}$, $V_{susc(yr)}$, V_{total}, $\log_{10}(M_{total}+3)$, $\log_{10}(M_{land}+3)$ and $\log_{10}(M_{non\text{-}land}+3)$ were entered into the Cox regression model in turn. The variables frequency and each of the six motion sickness susceptibility measures were entered in turn into the model and the variables giving the best overall fit (based on the chi-square statistic) were selected. In order to improve their distribution, the variables M_{total}, M_{land} and $M_{non\text{-}land}$ were logarithm (base 10) transformed prior to analysis (a constant of 3 was first added to avoid taking the logarithm of negative or zero values). The following variables were transformed to categorical variables prior to being entered into the Cox regression analysis[13]: frequency, $I_{susc(yr)}$ (4 categories: 0, $0 < I_{susc(yr)} \leq 0.120$, $0.120 < I_{susc(yr)} \leq 0.683$, $0.683 < I_{susc(yr)} \leq 1.67$), $V_{susc(yr)}$ (3 categories: 0, $0 < V_{susc(yr)} \leq 0.167$, $0.167 < V_{susc(yr)} \leq 1.67$), and V_{total} (4 categories: 0, 1, $2 \leq V_{total} \leq 6$, 7). The reference conditions for all the categorical variables entered into the model were the zero conditions (i.e. the cases when the variable of interest was 0).

Results

Table 8.2 gives the exponents of the regression coefficients and statistical significance for the variables remaining in the Cox regression model. The analysis discarded age, $I_{susc(yr)}$, $V_{susc(yr)}$, V_{total}, $\log_{10}(M_{total})$ and $\log_{10}(M_{non\text{-}land})$ from the model: these measures of motion sickness susceptibility did not significantly improve the predictive properties of the model.

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[13] Prior to transformation into categorical variables, the $I_{susc(yr)}$, $V_{susc(yr)}$, and V_{total} categories were determined using the 'visual bander' function supplied in the SPSS statistical software package (SPSS; version 12.0, SPSS, Chicago, IL). The cut-points between categories were selected automatically to be the 25th, 50th and 75th percentiles. To form variable categories that would be consistent across all investigations, the categorical variable transformation was applied to all 23 conditions reported in this thesis.

Table 8.2 Results of the Cox regression model (the variable 'compensation' was entered as a categorical variable in the analysis). † $p < 0.1$; * $p < 0.05$; ** $p < 0.01$.

Illness rating of interest, "3 – mild nausea"		
Overall: $\chi^2 = 35.962$, $p < 0.01$**		
Variable	Exp(ß)	*P*
Frequency	1.790	< 0.01**
Compensation	---	0.013*
25%	0.792	0.563
50%	0.804	0.423
75%	1.836	0.086†
100%	1.686	0.041*
$Log_{10}M_{land}$	3.377	< 0.01**

The total susceptibility to sickness in land transport, M_{land}, was a statistically significant predictor of reports of "3 – mild nausea": the exponent for this variable indicates that subjects reporting a susceptibility of 7 (corresponding to $\log_{10}(M_{land}+3) = 1$) would be roughly three times more likely to report "3 – mild nausea" than a subject reporting a susceptibility of -2 (corresponding to $\log_{10}(M_{land}+3) = 0$).

When entered as a categorical variable, the percentage compensation had a significant overall effect ($p < 0.01$). The relative risks indicate that exposure to either 25% or 50% roll-compensated oscillation was less likely to cause reports of "3 – Mild nausea" than pure lateral oscillation, although the differences were not significant. Both 75% and 100% roll-compensated lateral oscillations were more likely to provoke reports of "3 – Mild nausea" than pure lateral oscillation. With 75% compensation, the statistical differences were marginally significant and with 100% compensation they were significant: subjects would be between 65 to 85% more likely to report mild nausea with these motions than with the lateral oscillation without the roll motion. Subjects exposed to 0.2 Hz lateral oscillation were significantly more likely to report "3 – mild nausea" than subjects exposed to 0.1 Hz lateral oscillation ($p < 0.01$).

8.5 DISCUSSION

8.5.1 Effect percentage compensation

The median average illness ratings with each percentage and frequency of roll-compensated lateral oscillation are shown in Figure 8.5. The average illness ratings reported by subjects during exposure to 0.2 Hz lateral oscillation indicate that 0% and 100% roll-compensation caused more illness than 50% roll-compensation and these differences were, respectively, marginally and highly significantly different. Lateral oscillation with 100% roll compensation was the most nauseogenic condition.

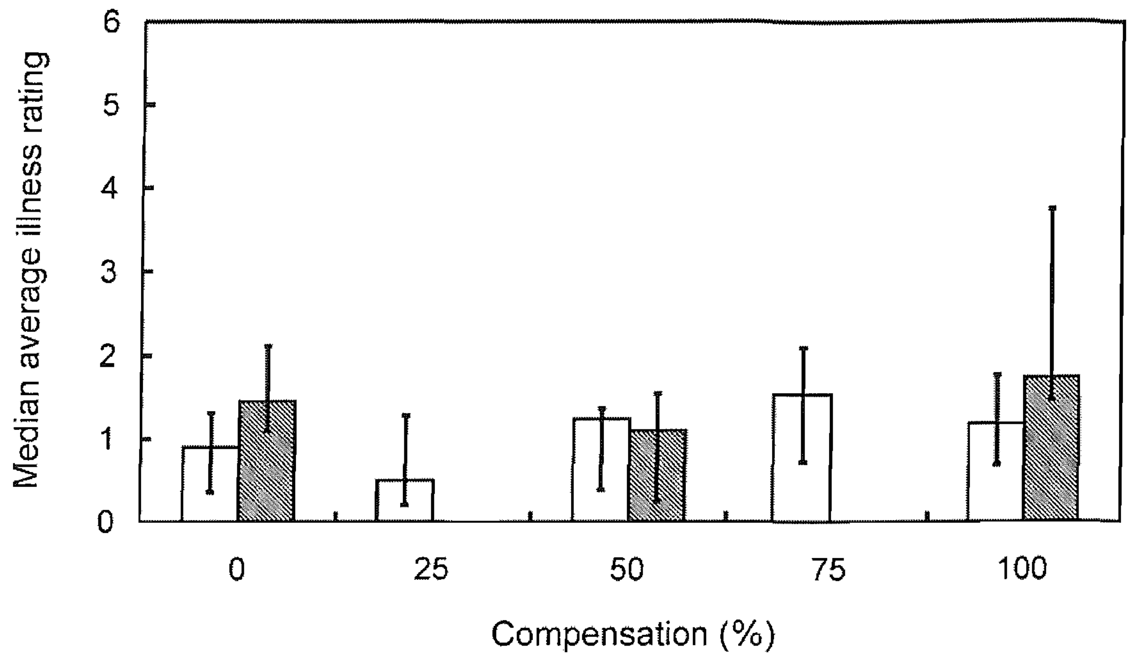

Figure 8.5 Median average illness ratings reported by the subjects for each percentage of roll-compensated with lateral oscillation at 0.1 and 0.2 Hz. Error bars indicate the inter-quartile range.

With 0.1 Hz lateral oscillation, the average illness ratings indicate that 25% and 50% roll-compensated lateral oscillation caused less motion sickness than uncompensated lateral oscillation, although the reduction was not statistically significant. Lateral oscillation at 0.1 Hz with 75% or 100% roll-compensation was significantly more likely to provoke reports of motion sickness than lateral oscillation with 25% roll-compensation. Motion sickness was least with 25% compensation and greatest with 75% compensation.

Similar findings were obtained with Cox regression analysis, indicating that motion sickness is dependent of the percentage of compensation; more illness was reported with increased roll-compensation. With both frequencies of oscillation it is possible that there is a trend of less sickness at an intermediate percentage of roll-compensation, but no significant differences were observed.

8.5.2 Effect of frequency

All the lateral oscillations in this investigation had the same peak acceleration magnitudes (± 1.26 ms^{-2}) but Cox regression showed that subjects more likely to report motion sickness with 0.2 Hz lateral oscillation than with 0.1 Hz oscillation. This finding may undermine the lateral acceleration frequency weighting for lateral oscillation proposed in Chapter 6, in which it was suggested that motion sickness was proportional to acceleration in this frequency range. The finding provides some evidence that the assumption of a linear effect of acceleration magnitude may be invalid over the range of magnitudes studied here.

8.5.3 Predicting motion sickness with combined lateral and roll oscillation

The observed effect of percentage compensation implies that motion sickness with combined lateral and roll oscillation may not be predicted simply by models with only lateral motion or only roll motion: with Earth-lateral oscillation of constant magnitude, increasing the percentage roll-compensation involves progressive increases in the roll displacement and progressive decreases in the peak lateral force felt by a subject. In contrast, changing the percentage roll-compensation did not result in a simple progressive increase or decrease in motion sickness. The effect of roll compensation cannot therefore be well-predicted by a linear function of either the roll displacement or the lateral force. The vertical acceleration experienced by subjects exposed to roll-compensated lateral oscillation also increases progressively with increasing roll displacement, and therefore also is insufficient to explain the observed variation in sickness with changes in roll compensation.

8.5.4 Application of findings

That motion sickness is dependent on the percentage of roll-compensation suggests that tilting-trains might be designed to provide optimum comfort in terms of reduced discomfort from vibration and reduced discomfort from motion sickness: with no compensation, discomfort from lateral forces is high and laboratory studies suggest that uncompensated lateral oscillation causes significant sickness and, therefore, significant discomfort; with 100% compensation, discomfort from lateral forces is eliminated but discomfort from motion sickness is greater than with uncompensated motion. Studies with 0.1 Hz and 0.2 Hz lateral oscillation over a range of compensations suggest that compensation can be used to minimise discomfort from motion sickness with resultant lateral forces that are less than those associated with uncompensated lateral acceleration.

8.6 CONCLUSIONS

With lateral oscillation at either 0.1 Hz or 0.2 Hz and roll-compensation in the range 0 to 100%, motion sickness was dependent on the percentage of roll-compensation. The effect of compensation on motion sickness cannot be simply predicted by models with only lateral motion or only roll motion. The findings may be of use in the design of tilting trains where minimal discomfort from vibration and minimal discomfort from motion sickness is required.

CHAPTER 9 DISCUSSION

9.1 INTRODUCTION

Findings from the literature review and the experimental work undertaken for this thesis are discussed here; part of the aim of the chapter is to reconcile these findings. A mathematical model capable of predicting motion sickness with motions other than those in the vertical axis has not been reported. A further aim of this chapter is to derive a motion sickness model, hypothesised on the basis of previous postulates, to predict quantitatively motion sickness with combined lateral and roll oscillations. Further sections discuss the strengths and weaknesses of the new model and, where necessary, review its assumptions, so as to provide recommendations for possible areas for future research.

9.2 MOTION SICKNESS MODELLING

9.2.1 Introduction

Neural mismatch, or sensory conflict, has been defined as arising from differences between sensed and expected afferent sensory information, the latter being determined by some central nervous process: e.g. central nervous system internal models of the physical world, such as those hypothesised in previous models by Oman (Oman, 1982) and Bos and Bles (Bos and Bles, 1998).

Both the sensed afferent information and the expected afferent information must be defined to predict motion sickness using neural mismatch mechanisms. The reviewed neural mismatch models have tended to differ in their definitions of the expected afferent signals, or some derivative of these, such as estimates of orientation and linear acceleration. Of these models, only one, the subjective vertical model, has been used to make quantitative predictions of neural mismatch (Bles *et al.*, 1998); however, the Bos and Bles subjective vertical model has not been extended to motions in axes other than the vertical.

It is hypothesised that Stott's postulates (Stott, 1986), can be developed to allow quantitative predictions of motion sickness using a vector expression to quantify the degree of neural mismatch for combined lateral and roll oscillations. Although Stott postulated that motion sickness arises from both visual and vestibular interactions, it is assumed that the important interaction for the studies reported here is an intra-vestibular interaction arising from the interpretation of the gravito-inertial force (i.e. the resultant force acting on a body arising from the force due to gravity and the force due to acceleration): in these experimental studies the visual scene was the same for every subject. It is suggested that Stott's 2nd and 3rd postulates describe intra-vestibular interactions, which define expected relationships in angular and linear motion arising from changes in the magnitude and direction of the gravito-inertial force at low frequencies.

9.2.2 Extrapolation of Stott's 2nd and 3rd postulates

Introduction

In his addition to the sensory-rearrangement theory of motion sickness, Stott postulated that three sensory interactions were sufficient to cause motion sickness. The aim of this section is to develop the two postulated vestibular interactions, so as to allow the formulation of a quantitative model of motion sickness for motions in more than one axis (i.e. for combined lateral and roll oscillations).

Quantitative development of Stott's 'canal-otolith interaction' postulate

Stott's 2nd postulate stated the following:

> "Rotation of the head, other than in the horizontal plane, must be accompanied by an appropriate angular change in the direction of the linear acceleration due to gravity."

The statement postulates an expectation of a change in the direction of the gravity force resulting from a change in orientation of a body with respect to the Earth. It can be assumed that rotations causing changes in orientation with respect to the Earth are estimated from semicircular canal stimulation and that the resulting changes in the direction of the gravito-inertial force are derived from otolith stimulation.

For a quantitative interpretation of the postulate, it is assumed that a neural mismatch, causing motion sickness, arises from the sensory interaction and is quantified by calculating an angular orientation error, e_φ: the error is expressed as the angular difference between the orientation with respect to the Earth expected from otolith organ sensation, φ_{oto}, and that estimated from semicircular canal sensation, φ_{scc}:

$$e_\varphi = \varphi_{oto} - \varphi_{scc}$$

Combined lateral and roll oscillations cause changing forces in the lateral and vertical axes of a subject, such that the expected resultant force sensed by the otoliths can be described by a vector, f_{oto}, given by:

$$f_{oto} = \begin{bmatrix} f_{y,oto} \\ f_{z,oto} \end{bmatrix}$$

For the case of combined lateral and roll oscillations, the direction of the resultant force vector with respect to the head, as sensed by the otoliths, f_{oto}, can be calculated from the arc tangent of the component lateral force, $f_{y,oto}$, and vertical force, $f_{z,oto}$ (which, according to Stott's 3rd postulate, are assumed to indicate the direction of the resultant gravito-inertial force over time periods greater than one second):

$$\varphi_{oto} = \arctan\left(\frac{f_{y,oto}}{f_{z,oto}}\right)$$

Thus, if the orientation of the head relative to the gravito-inertial force determined by the otoliths (φ_{oto}) is used to estimate the expected orientation of the head with respect to the Earth, then the angular orientation error becomes

$$e_{\varphi} = \arctan\left(\frac{f_{y,oto}}{f_{z,oto}}\right) - \varphi_{scc}$$

Quantitative development of Stott's 'utricle-saccule interaction' postulate

Stott's 3rd postulate stated the following:

> "Any sustained linear acceleration (duration > 1 s) is due to gravity, has an intensity of 1 g (9.81 ms^{-2}) and defines "downwards."

The postulate assumes that, when sensed by the otoliths and averaged over time periods greater than one second, the magnitude of the gravito-inertial force vector must be equal to the magnitude of the force due to gravity, -9.81 ms^{-2}.

The postulate suggests a second neural mismatch causing a gravito-inertial force magnitude error. The error is expressed as the magnitude difference between the magnitude of the resultant (or gravito-inertial) force sensed by the otoliths, f_{oto}, and the magnitude of the expected force (-9.81 ms^{-2}).

For combined translational and roll motions, causing changes in the lateral and vertical forces felt by subjects, the magnitude of the gravito-inertial force vector sensed by the otoliths, f_{oto}, is given by:

$$|f_{oto}| = \sqrt{f_{y,oto}^2 + f_{z,oto}^2}$$

The resultant force expected to act at the head can be represented as a vector, f_{scc}. With combined lateral and roll oscillations, the expected force vector has components in the lateral and vertical axes; where the expected lateral force is denoted $f_{y,scc}$ and the expected vertical force is denoted $f_{z,scc}$. The expected force components are hypothesised as being estimated directly from semicircular canal sensation of the orientation of the head with respect to the Earth[14], φ_{scc}:

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[14] Section 2.4.3 (Chapter 2) reports that the semi-circular canals operate as rate sensors, such that they respond to angular velocity. If it is hypothesised that semi-circular canal sensation is used to

$$f_{scc} = \begin{bmatrix} f_{y,scc} \\ f_{z,scc} \end{bmatrix} = \begin{bmatrix} g \cdot \sin\varphi_{scc} \\ g \cdot \cos\varphi_{scc} \end{bmatrix}$$

Thus, the magnitude of the expected resultant force, arising from the expected forces in the lateral and vertical axes, is given by:

$$\begin{aligned} |f_{scc}| &= \sqrt{f_{y,scc}^2 + f_{z,scc}^2} \\ |f_{scc}| &= g \cdot \sqrt{\sin^2\varphi_{scc} + \cos^2\varphi_{scc}} \\ |f_{scc}| &= g \end{aligned}$$

It follows that the error (or mismatch) between the sensed and expected gravito-inertial force magnitudes is given by:

$$\begin{aligned} e_{|\,|} &= |f_{oto}| - |f_{scc}| \\ e_{|\,|} &= \sqrt{f_{y,oto}^2 + f_{z,oto}^2} - \sqrt{f_{y,scc}^2 + f_{z,scc}^2} \\ e_{|\,|} &= \sqrt{f_{y,oto}^2 + f_{z,oto}^2} - g \end{aligned}$$

9.2.3 Development of quantitative model of motion sickness from Stott's 2nd and 3rd postulates

Rationale

Stott's 2nd and 3rd postulates describe situations of neural mismatch arising from vestibular organ sensation: the two postulates have been interpreted as describing a magnitude error and a direction error arising from the sensed and expected forces determined from otolith and semi-circular canal sensation.

This section extrapolates from the two postulates a gravito-inertial force neural mismatch model based on the vector difference between the estimates of the sensed forces and expected forces; the latter being estimated from changes in orientation with respect to the Earth-vertical axis. The initial model attempts to predict motion sickness with combined lateral and roll oscillation. Therefore, it is defined for translational motions in the plane defined by the Earth-lateral and Earth-vertical axes and rotational motions about the orthogonal Earth-horizontal axis.

Statement of initial model

It is hypothesised that motion sickness is dependent on the resultant magnitude of the vector difference between the sensed and expected subject-referenced forces. The

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determine the orientation of the body with respect to the Earth, then it must be assumed that a neural mechanism acts to integrate the semi-circular canal information from a known starting position.

sensed force, f_{oto}, has the magnitude and direction of the gravito-inertial force, as sensed by the otoliths. The expected force, f_{scc}, is that due to gravity, such that its magnitude is constant (-9.81 m/s²) and its direction is given by the orientation of the body with respect to the Earth-vertical, as estimated from semicircular canal sensation.

Vector notation is used to express the model, such that it gives an error for each subject-referenced axis:

$$e = f_{oto} - f_{scc}$$

$$\begin{bmatrix} e_y \\ e_z \end{bmatrix} = \begin{bmatrix} f_{y,oto} \\ f_{z,oto} \end{bmatrix} - \begin{bmatrix} f_{y,scc} \\ f_{z,scc} \end{bmatrix}$$

$$\begin{bmatrix} e_y \\ e_z \end{bmatrix} = \begin{bmatrix} f_{y,oto} \\ f_{z,oto} \end{bmatrix} - \begin{bmatrix} g.\sin\varphi_{scc} \\ g.\cos\varphi_{scc} \end{bmatrix}$$

$$\begin{bmatrix} e_y \\ e_z \end{bmatrix} = \begin{bmatrix} f_{y,oto} - g.\sin\varphi_{scc} \\ f_{z,oto} - g.\cos\varphi_{scc} \end{bmatrix}$$

The magnitude of the mismatch is hypothesised to be dependent on the magnitude of the vector difference, or error, as suggested by previous models of sensory conflict (e.g. Bos and Bles, 1998):

$$|e| = \left[\left(f_{y,oto} - f_{y,scc}\right)^2 + \left(f_{z,oto} - f_{z,scc}\right)^2\right]^{1/2}$$

Model assumptions

In order to calculate predictions of motion sickness, several assumptions are necessary to simplify and refine the model. The aim of the assumptions is to provide a model that is conceptually (i.e. functionally) and computationally straightforward. The assumptions, including those assumptions already implied in the definition of the model, are stated here without rationale: a critique of these assumptions forms the basis of the final discussion section of this thesis.

1. The measure of illness of interest is the proportion of subjects to have reported an illness rating of "3: Mild nausea" during a 30-minute exposure to combined lateral and roll oscillation
2. The incidence of illness is proportional to the magnitude of the error (or mismatch) as calculated by the model.
3. There is no effect of vision.
4. In the studies reported in this thesis the combined lateral and roll oscillations had a constant phase relationship; i.e., the Earth-lateral forces and roll displacements

were in phase. In this initial implementation of the model there are no mechanisms to account for any possible effects of phase.

5. Other than assuming that motion sickness is caused by oscillations at frequencies less than 1.0 Hz, the model initially will not assume any frequency dependence of motion sickness: i.e. there is no filtering or frequency-weighting of the component motion variables.

6. The effects of duration of exposure, adaptation or habituation have not been studied and are not included in the model.

7. The force at the seat surface will be considered, as opposed to the forces at the head: the centre of roll was at the centre of the seat surface and tangential and centrifugal forces due to rotational motion of a subject's head are assumed insignificant, as the oscillation frequencies were less than 0.8 Hz.

8. As the subjects sat upright, with a low back rest, it is assumed that subjects can be treated as a rigid body at low frequencies, such that there was no influence of posture.

9. The model will be used to predict motion sickness with oscillations having constant peak amplitude during each motion exposure.

10. The otolithic signals in the lateral and vertical axes are assumed to be linearly related to the actual subject-referenced force components arising from acceleration and gravity in these axes (denoted by f_y' and f_z' respectively):

$$f_{y,oto} = k_{y,oto} \cdot f_y'$$
$$f_{z,oto} = k_{z,oto} \cdot f_z'$$

11. Given a known starting position, it is assumed that the orientation of the head with respect to the Earth, φ, can be estimated without error from appropriate integration of the semi-circular canal information:

$$\varphi = \varphi_{scc}$$

12. Similarly, the forces expected in the lateral and vertical axes are assumed to be linearly related to the forces arising from changes in the orientation of head with respect to the force due to gravity:

$$f_{y,scc} = k_{y,scc} \cdot g \cdot \sin\varphi$$
$$f_{z,scc} = k_{z,scc} \cdot g \cdot \cos\varphi$$

Thus, the model predicts that the magnitude of the error (or mismatch) is given by

$$|e| = \left[\left(k_{y,oto} \cdot f_y' - k_{y,scc} \cdot g \cdot \sin\varphi\right)^2 + \left(k_{z,oto} \cdot f_z' - k_{z,scc} \cdot g.\cos\varphi\right)^2\right]^{1/2} \quad \text{Equation 1}$$

9.2.4 Development of motion sickness model for lateral and roll oscillations

Force environment characterisation for lateral and roll oscillations

If the Earth-lateral and Earth-vertical gravito-inertial forces are given by f_y and f_z, then, when rotated by an angle, φ, about the x-axis relative to the Earth-referenced coordinate system, the subject-referenced forces are given by

$$f_y' = f_y \cdot \cos\varphi + f_z \cdot \sin\varphi$$
$$f_z' = -f_y \cdot \sin\varphi + f_z \cdot \cos\varphi$$

For small angles, the roll angle of the subject about the Earth's x-axis, φ, can be approximated using:

$$\sin\varphi \approx \varphi$$
$$\cos\varphi \approx 1$$

Using the small angle approximation, the expressions describing the subject-referenced forces are simplified:

$$f_y' = f_y + f_z \cdot \varphi$$
$$f_z' = -f_y \cdot \varphi + f_z$$

After substitution of the subject-referenced forces, Equation 1 simplifies to the following expression:

$$|e| = \left[\left(k_{y,oto} \cdot f_y' - k_{y,scc} \cdot g \cdot \varphi\right)^2 + \left(k_{z,oto} \cdot f_z' - k_{scc} \cdot g\right)^2 \right]^{1/2} \qquad \text{Equation 2}$$

Motion sickness model for roll-compensated lateral oscillation

The model, given by equation 2, can be simplified further for the case of roll-compensated lateral oscillation. With these conditions, the Earth-referenced forces are given by

$$f_y = -a_y$$
$$f_z = g$$

Where, a_y is the Earth-lateral acceleration and g is the force due to gravity.

The subject-referenced forces are governed by the compensation ratio, p, which in turn determines the orientation of a subject relative to the Earth; the roll angle is a function of the Earth-lateral force, f_y, and the compensation ratio, and is referenced relative to the Earth-vertical. Thus for roll-compensated lateral oscillation, the roll angle of the subject about the Earth's x-axis, φ, is given by:

$$\varphi = -\arctan\left(\frac{f_y \cdot p}{g}\right)$$

It follows that the cosine and sine of the angle of the subject relative to the Earth-vertical, φ, are given by:

$$\sin\varphi = -\frac{f_y \cdot p}{g}$$

$$\cos\varphi = 1$$

As the angle of a subject relative to the Earth-vertical, φ, is small (of the order 10° or less for the roll-compensated lateral oscillations studied in this thesis), small angle approximations can be assumed[15], such that:

$$\varphi = -\frac{f_y \cdot p}{g}$$

Similarly, for a compensation ratio, p, the subject-lateral and vertical forces are given as follows:

$$f_y' = f_y \cdot (1-p)$$
$$f_z' = g$$

An expression predicting motion sickness with roll-compensated lateral oscillation is given by substituting the appropriate approximations for the subject-referenced forces and the cosine and sine of the orientation (roll angle) of the subject with respect to the Earth, into Equation 2:

$$|e| = \left[f_y^2 \cdot \left(k_{y,oto} \cdot (1-p) + k_{y,scc} \cdot p\right)^2 + g^2 \cdot \left(k_{z,oto} - k_{z,scc}\right)^2\right]^{1/2} \quad \text{Equation 3}$$

The expression given by Equation 3, suggests that motion sickness with roll-compensated lateral oscillation is dependent on the variables representing the Earth-lateral force, f_y, and the desired compensation ratio, p.

9.2.5 Model implementation

One implementation of the model might continuously predict motion sickness from the error (or mismatch), which changes as the subject-referenced lateral and vertical forces vary as a function of time. With the studies reported in this thesis, the combined lateral and roll oscillations were in phase, such that the Earth-referenced lateral forces and roll displacements were in phase. A time–dependent motion sickness model for in-phase roll-

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[15] As a consequence of the small angle approximations, the following relationships are assumed true for the roll-compensated lateral oscillations investigated in this thesis: $f_y << f_z$ (i.e. the ratio of the Earth-lateral force to the force due to gravity is small) and $f_y' << f_z'$ (i.e. the ratio of the lateral and vertical forces in the subject-referenced axes also is small).

compensated harmonic lateral oscillations, predicts an error (or mismatch), $|e(t)|$, that varies as a function of the time-varying lateral force:

$$|e(t)| = \left[f_{y0}^2 \cdot \sin^2 \omega t \cdot \left(k_{y,oto} \cdot (1-p) + k_{y,scc} \cdot p\right)^2 + g^2 \cdot \left(k_{z,oto} - k_{z,scc}\right)^2\right]^{1/2} \qquad \text{Equation 4}$$

Where the Earth-lateral force is given by

$$f_y(t) = f_{y0} \cdot \sin \omega t$$

and has an angular frequency, ω, and an amplitude, f_{y0}.

With these harmonic lateral oscillations, the variables representing the amplitude of the Earth-lateral force, f_{y0}, and the compensation ratio, p, are constant and the error predicted by the model $|e(t)|$, varies as a sinusoidal function with an amplitude given by the following relationship:

$$|e| \propto f_{y0} \cdot \left(k_{y,oto} \cdot (1-p) + k_{y,scc} \cdot p\right)$$

Given this expression, it is suggested that the peak amplitude of the subject-lateral force, f_{y0}, can be used to represent the magnitude of motion exposure, such that the model will predict the peak error for each condition; as the error is a periodic function of time, the peak error represents the overall magnitude of error and thus the potential nauseogenicity of the combined lateral and roll oscillations. Thus, for the remainder of this chapter the following expression will be used to predict motion sickness with roll-compensated lateral oscillation:

$$|e| = \left[f_{y0}^2 \cdot \left(k_{y,oto} \cdot (1-p) + k_{y,scc} \cdot p\right)^2 + g^2 \cdot \left(k_{z,oto} - k_{z,scc}\right)^2\right]^{1/2} \qquad \text{Equation 5}$$

where f_{y0} is the amplitude of the Earth-lateral force and p is the compensation ratio.

A benefit of using single values to represent the magnitude of the motion exposure (e.g. the peak lateral force), is that the model can be optimised by adjusting the model parameters so as to fit the predicted conflict to the proportion of subjects reporting an illness rating of “3: Mild nausea”. A ‘Solver’ optimisation tool in the Excel software package (Microsoft ® Office Excel 2003; Copyright © Microsoft Corporation 1985 – 2003) was used to complete this task for various sets of experimental results obtained with combined lateral and roll oscillations. By adjusting the model parameters, the Solver tool was used to minimise the root-mean-squared error between model predictions of motion sickness, represented by the magnitude of the model error, $|e|$, and the proportions of subjects reporting “3: Mild nausea” within various different groups of experimental conditions. The goodness of fit of the model was evaluated using a Pearson correlation coefficient.

9.3 PREDICTIONS OF MOTION SICKNESS

9.3.1 Introduction

For each experiment in turn, the model is fitted to the data from the laboratory studies investigated in this thesis, such that an optimised set of model parameters is estimated for each type of motion studied (i.e. one set of parameters for conditions of pure lateral oscillation; another set for conditions of fully roll-compensated lateral oscillation and so on). For each type of motion, predictions of motion sickness are also obtained from examination of the analytical behaviour of the model.

Where appropriate, a set of optimised model parameters for groups of conditions involving more than one type of motion are obtained (e.g. a set of model parameters optimised to fit the reports of motion sickness with both uncompensated and fully roll-compensated lateral oscillations).

Finally, predictions of motion sickness with pure vertical oscillations and pure roll oscillations are compared to the data obtained in previous experiments. The section concludes with a parameter fit to all the available data from studies of lateral and roll (but not vertical) oscillation.

9.3.2 Predictions of motion sickness with the conditions of lateral and roll oscillation studied in the laboratory

Functional analysis of model for pure lateral oscillation

When p = 0 (representing the case of pure Earth-lateral oscillation), the model (expressed as Equation 5) reduces to

$$|e| = \left[k_{y,oto}^2 \cdot f_{y0}^2 + g^2 \cdot (k_{z,oto} - k_{z,scc})^2\right]^{1/2} \quad \text{Equation 6}$$

As the values of g, and the gains $k_{y,oto}$, $k_{z,oto}$, and $k_{z,scc}$ are assumed constant, the model predicts that motion sickness with pure lateral oscillation is dependent on the magnitude of the Earth-lateral force, which in turn depends on the Earth-lateral acceleration, $f_y = -a_y$. The expression representing the model has a form equivalent to the equation for the magnitude of the gravito-inertial force:

$$|e| \propto \left[f_{y0}^2 + g^2\right]^{1/2}$$

Equation 6 predicts that motion sickness with lateral oscillation will increase as the resultant force increases, rather than increasing linearly with increasing Earth-lateral force (or, therefore, the magnitude of Earth-lateral acceleration).

Table 9.1 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposure to pure lateral oscillation.

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
0.334	3.707	0.000	3.707	0.109	0.726

Quantitative model predictions for pure lateral oscillation

The mismatch (|e|) predicted by Equation 5 was fitted to the proportions of subjects reporting "3: Mild nausea" during the conditions of pure lateral oscillation conducted for the purposes of this thesis (reported in Chapters 6 and 8). With these conditions (10 conditions in total), the acceleration magnitude varied with frequency (see Tables 6.1 and 8.1). The model parameters giving the best fit to the data are shown in Table 9.1. The root-mean-square error and correlation coefficient arising from the optimisation process are also given. Figure 9.1 compares as a function of frequency the predictions and measurements of the proportions of subjects reporting "3: Mild nausea".

Figure 9.1 illustrates that the model could be fitted to the trends in motion sickness observed with pure lateral oscillations (i.e. as the oscillation magnitude varied with frequency then so did motion sickness) and the model predictions were correlated with measured reports of "3: Mild nausea".

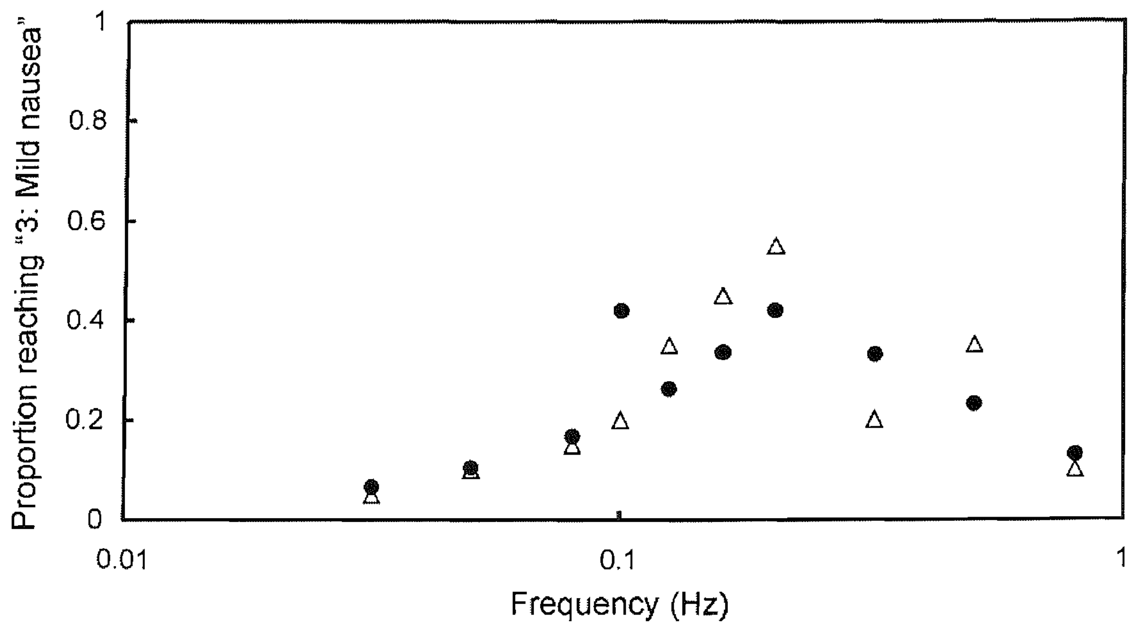

Figure 9.1 Predicted and measured proportions of subjects reporting "3: Mild nausea" during exposure to pure lateral oscillation, as a function of oscillation frequency. Solid black circles: predicted proportion of subjects reporting "3: Mild nausea"; Open triangles: measured proportion of subjects reporting "3: Mild nausea".

As expected from the functional analysis of the model (e.g. Equation 6), the parameter $k_{y,scc}$ did not influence model predictions, and the optimisation showed that the sensitivity to motion sickness was dependent on the gain $k_{y,oto}$.

The model parameters $k_{z,oto}$ and $k_{z,scc}$ were approximately equal (to 3 decimal places), such that, when combined with the force due to gravity (as in Equation 6), the rate of increase of motion sickness with increasing Earth-lateral oscillation magnitude, f_{y0}, decreases with increasing magnitude (i.e. as the lateral force amplitude, f_{y0}, approaches infinity then the relationship between the lateral force, f_{y0}, and the error given by Equation 6 approaches linearity).

Motion sickness with pure lateral oscillation at 0.1 Hz was not well predicted, suggesting that the effect of oscillation magnitude predicted by the model was not in itself sufficient to predict motion sickness; the model does not contain any frequency dependent terms: with the condition involving oscillation at 0.1 Hz, the magnitude of oscillation was equivalent to that studied with oscillation at 0.2 Hz, and the model predicts equivalent motion sickness for both conditions. It is suggested that the absence of frequency-dependent terms in the model may account for the erroneous prediction and that a model including terms to predict both the effect of frequency and the effect of magnitude may better predict motion sickness.

Functional analysis of model for fully roll-compensated lateral oscillation

When p = 1 (100% compensation), the model given by Equation 5 reduces to

$$|e| = \left[k_{y,scc}^2 \cdot f_{y0}^2 + g^2 \cdot \left(k_{z,oto} - k_{z,scc}\right)^2\right]^{1/2} \quad \text{Equation 7}$$

As the values of g, and the parameters $k_{y,scc}$, $k_{z,oto}$, and $k_{z,scc}$ are assumed constant, Equation 7 suggests that motion sickness with fully roll-compensated lateral oscillation changes with changing magnitude of the Earth-lateral force (and therefore the Earth-lateral acceleration). As observed with pure Earth-lateral oscillations, the expression representing the model with fully roll-compensated lateral oscillations has a form similar to that representing the magnitude of the gravito-inertial force; however, the model predicts instead that the sensitivity to motion sickness is dependent on the gain $k_{y,scc}$ (i.e. the sensitivity to the expected force in the subject-lateral y-axis).

Quantitative model predictions for fully roll-compensated lateral oscillation

The mismatch ($|e|$) predicted by Equation 5 was fitted to the proportions of subjects reporting "3: Mild nausea" during the conditions of fully roll-compensated lateral oscillation (reported in Chapters 7 and 8). With these conditions (9 conditions in total), the lateral acceleration magnitudes varied with frequency (see Tables 7.1 and 8.1) and were the same as those used with pure lateral oscillations.

Table 9.2 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposure to fully roll-compensated lateral oscillation.

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
0.000	0.000	0.432	0.024	0.133	0.651

The model parameters giving the best fit to the proportions of subjects reporting "3: Mild nausea" during exposure to fully roll-compensated lateral oscillations are shown in Table 9.2. The root-mean-square error and correlation coefficient arising from comparisons between the predicted and measured reports of "3: Mild nausea" are also given. Figure 9.2 compares the predicted and measured reports of "3: Mild nausea" for each of the studied frequencies of lateral oscillation.

Figure 9.2 illustrates that the model could be fitted to trends in the reports of "3: Mild nausea" with fully roll-compensated lateral oscillations, such that the actual reports and model predictions were highly correlated. As observed with model predictions of motion sickness with 0.1 Hz pure lateral oscillation, reports of "3: Mild nausea" with 0.1 Hz fully roll-compensated lateral oscillation were not well predicted. When fitted to the fully roll-compensated lateral oscillation data, the resultant model parameters, $k_{y,scc}$ and $k_{z,scc}$, suggest that motion sickness was dependent on the expected lateral and vertical forces, which in the development of the model were hypothesised as being determined from sensations related to the roll angle relative to the Earth-referenced coordinate system.

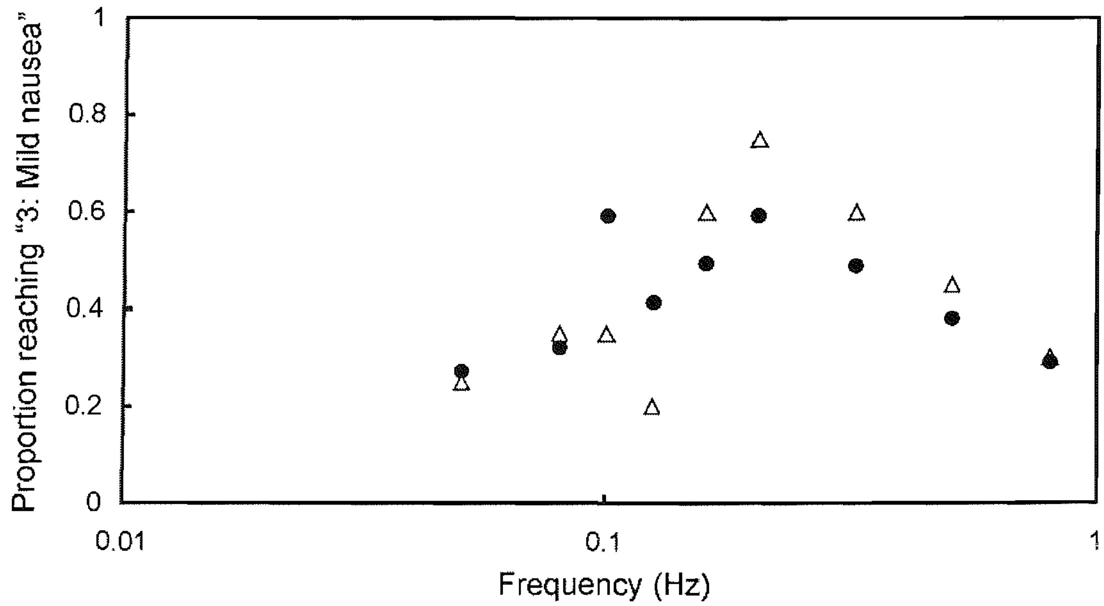

Figure 9.2 Predicted and measured proportions of subjects reporting "3: Mild nausea" during exposure to fully roll-compensated lateral oscillation. Solid black circles: predicted proportion of subjects reporting "3: Mild nausea"; Open triangles: measured proportion of subjects reporting "3: Mild nausea".

Table 9.3 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposure to 0% and 100% roll-compensated lateral oscillations.

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
0.310	-0.003	0.490	0.008	0.126	0.745

Model parameter fitting for motion sickness with uncompensated and fully roll-compensated lateral oscillations

The model parameters giving the best fit of Equation 5 to the proportions of subjects reporting "3: Mild nausea" during exposures to the conditions of uncompensated and fully roll-compensated lateral oscillation studied in this thesis (with motion parameters reported in Tables 6.1, 7.1 and 8.1) are shown in Table 9.3. The root-mean-square error and correlation coefficient arising from comparisons between the predicted and measured reports of "3: Mild nausea" are also given. Figure 9.3 shows the correlation between the predicted and measured reports of "3: Mild nausea" for conditions involving uncompensated and fully roll-compensated lateral oscillation.

Figure 9.3 and the correlation coefficient in Table 9.3 illustrate that the model can be fitted to simultaneously predict the trends in motion sickness observed with uncompensated and fully roll-compensated lateral oscillations at various frequencies and magnitudes.

Differences between the model parameters $k_{y,oto}$ and $k_{y,scc}$ with uncompensated and fully roll-compensated lateral oscillations suggest that susceptibility to motion sickness is more strongly dependent on the expected force in the subject-lateral axis than the measured force in the subject-lateral axis (i.e. the modulus of $k_{y,scc}$ is greater than the modulus of $k_{y,oto}$).

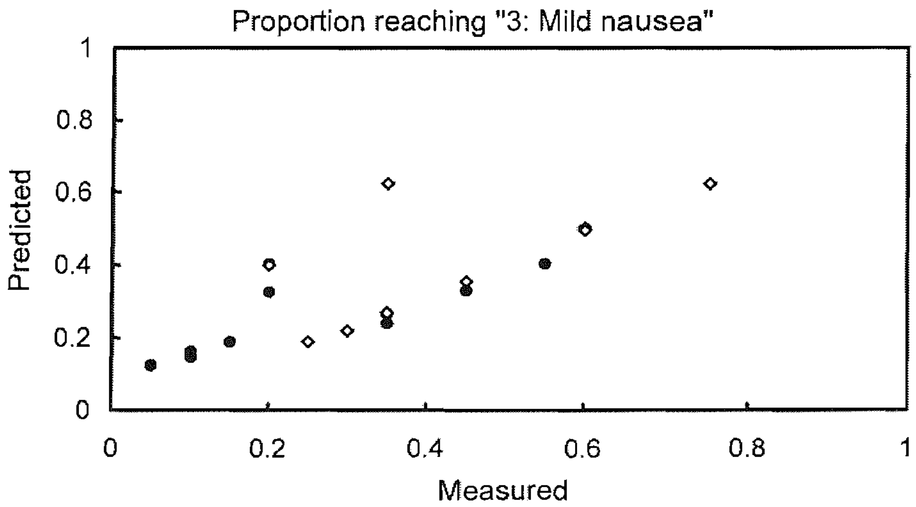

Figure 9.3 Correlation between the predicted and measured proportions of subjects reporting "3: Mild nausea" during exposure to uncompensated and fully roll-compensated lateral oscillations. Solid black circles: uncompensated lateral oscillation; Open diamonds: fully roll-compensated lateral oscillation.

Functional analysis of model predictions of the effect of the percentage of roll-compensation

It can be investigated whether the model can fit a trend showing minimum motion sickness (and, therefore, minimum mismatch or error, $|e|$) with roll-compensation ratios, p, in the range $0 \leq p \leq 1$. When the Earth-lateral force amplitude, f_{y0}, is held constant, and the values of g, and the parameters $k_{z,oto}$, and $k_{z,scc}$ are assumed constant, the model (Equation 5) predicts that mismatch is dependent on the compensation ratio, p, Equation 5 suggests that the mismatch or error is minimised when the following expression is true:

$$k_{y,oto} \cdot (1-p) + k_{y,scc} \cdot p = 0$$

Or alternatively:

$$k_{y,oto} + p \cdot (k_{y,oto} - k_{y,scc}) = 0 \quad \text{Equation 8}$$

If the model parameters $k_{y,oto}$ and $k_{y,scc}$ are both positive, then there is no minimum in the range $0 \leq p \leq 1$: when fitted to reports of motion sickness obtained from groups of subjects exposed to either or both uncompensated and fully roll-compensated lateral oscillations, the model parameters $k_{y,oto}$ and $k_{y,scc}$ were positive (see Tables 9.1 to 9.3); so, the parameters obtained from these fits are unlikely to predict motion sickness with intermediate compensation ratios.

A minimum in motion sickness will exist if either $k_{y,oto}$ or $k_{y,scc}$ is negative. When the roll-compensation ratio, p, increases in the range from 0 to 1, the model must predict a minimum in motion sickness at some compensation, defined as $p_{|e|=\min}$, to fit the trend observed in the laboratory studies. Equation 8 can be re-arranged to find the compensation, $p_{|e|=\min}$, at which the model error will be minimised (when either $k_{y,oto}$ or $k_{y,scc}$ is negative):

$$p_{|e|=\min} = \frac{|k_{y,oto}|}{|k_{y,oto}| + |k_{y,scc}|} \qquad \text{Equation 9}$$

The expression given by Equation 9 can be used to predict the compensation ratio at which motion sickness is a minimum and implies that if $|k_{y,scc}| > |k_{y,oto}|$, then fully roll-compensated lateral oscillation will be more nauseogenic than pure lateral oscillation. Furthermore, if $|k_{y,scc}| > |k_{y,oto}|$, then the denominator of the expression for $p_{|e|=\min}$ will always be greater than twice the numerator, predicting that minimum motion sickness will occur when the compensation ratio is in the range $0 \leq p \leq 0.5$. Similar findings were observed during the experimental studies of the effect of roll-compensation.

Table 9.4 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposure to various percentages of compensation with 0.2 Hz lateral oscillation.

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
0.435	2.916	-0.425	2.909	0.000	1.000

Quantitative model predictions of the effect of the percentage of roll-compensation

Predictions of mismatch (from Equation 5), $|e|$, were fitted to the proportions of subjects reporting "3: Mild nausea" during investigations of the effect on motion sickness of the percentage of roll-compensation with lateral oscillations at 0.1 and 0.2 Hz. The eight conditions of interest were reported in Chapter 8 and their motion magnitudes given in Table 8.1.

Three fits, producing three sets of optimised parameters, were calculated: the first set was fitted to the three conditions studied with 0.2 Hz oscillation; the second set was fitted to the five conditions involving oscillation at 0.1 Hz; and the third set was fitted to all eight conditions.

The model parameters resulting in the best fit to the proportions of subjects reporting "3: Mild nausea" during exposures to various percentages of roll-compensation with 0.2 Hz lateral oscillation are shown in Table 9.4. The root-mean-square error and correlation coefficient arising from comparisons between the predicted and measured reports of "3: Mild nausea" are also given. Figure 9.4 compares the predicted and measured reports of "3: Mild nausea" for each percentage of roll-compensation.

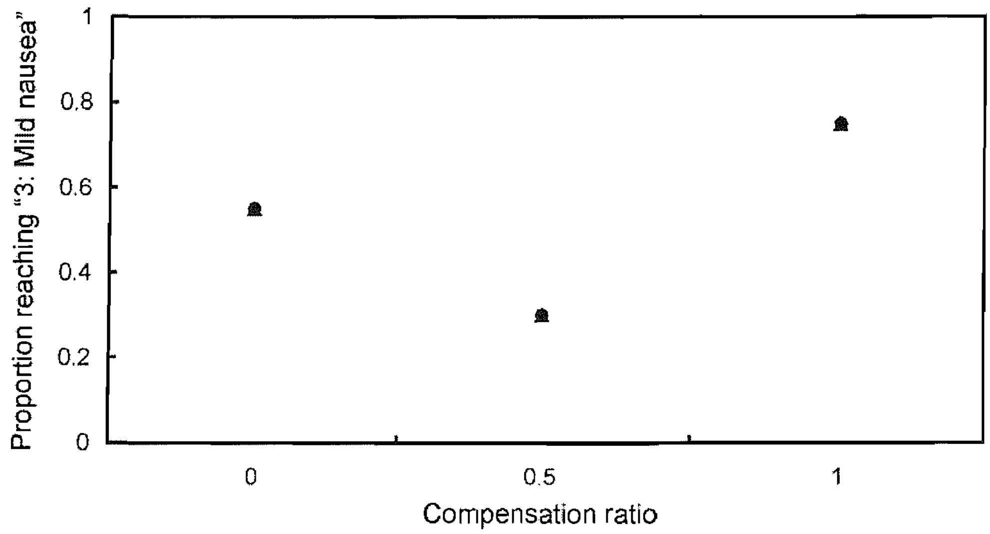

Figure 9.4 Predicted and measured proportions of subjects reporting "3: Mild nausea" as a function of percentage roll-compensation with 0.2 Hz lateral oscillations. Solid black circles: predicted proportion of subjects reporting "3: Mild nausea"; Open triangles: measured proportion of subjects reporting "3: Mild nausea".

Table 9.5 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposure to various percentages of compensation with 0.1 Hz lateral oscillation.

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
-0.050	1.458	0.352	1.477	0.103	0.711

As only three conditions involved oscillation at 0.2 Hz, and given that Equation 5 has four parameters, it is likely that the parameters given in Table 9.4 will always produce a perfect fit. In this case the optimisation error and correlation are not meaningful; although, the model parameters remain valid.

The model parameters giving the best fit to the proportions of subjects reporting "3: Mild nausea" during exposures to various percentages of roll-compensation with 0.1 Hz lateral oscillation are shown in Table 9.5. The root-mean-square error and correlation coefficient arising from comparisons between the predicted and measured reports of "3: Mild nausea" are also given. Figure 9.5 compares the predicted and measured reports of "3: Mild nausea" for each percentage of roll-compensation.

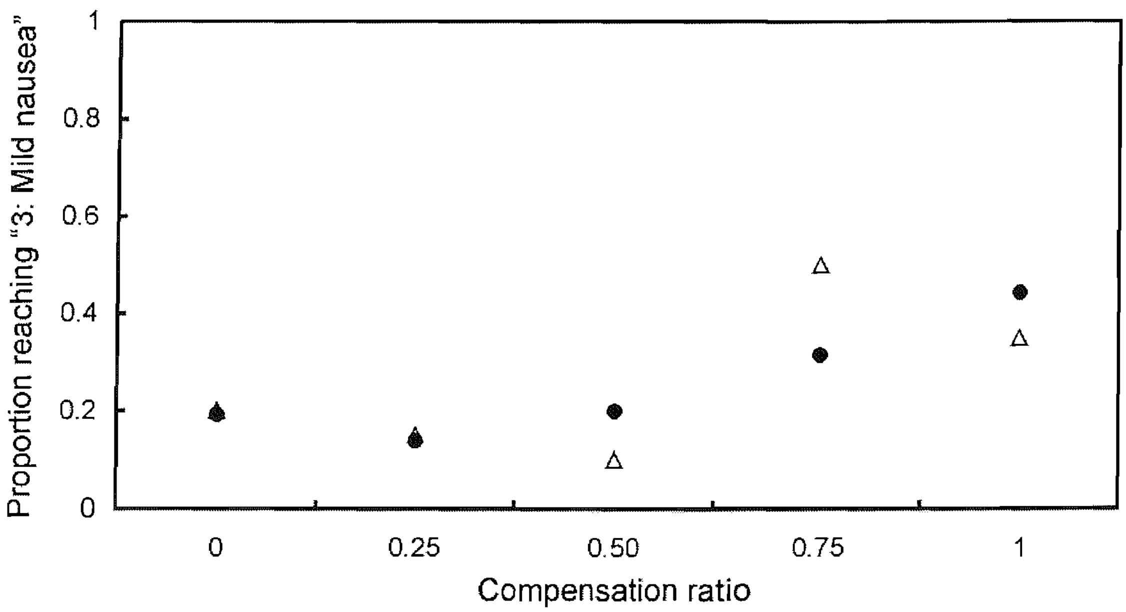

Figure 9.5 Predicted and measured proportions of subjects reporting "3: Mild nausea" as a function of percentage roll-compensation with 0.1 Hz lateral oscillations. Solid black circles: predicted proportion of subjects reporting "3: Mild nausea"; Open triangles: measured proportion of subjects reporting "3: Mild nausea".

Table 9.6 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposure to various percentages of compensation with 0.1 and 0.2 Hz lateral oscillations.

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
0.281	1.933	-0.381	1.928	0.150	0.696

The model parameters giving the best fit to the proportions of subjects reporting "3: Mild nausea" during exposures to various percentages of roll-compensation with both 0.1 and 0.2 Hz lateral oscillation are shown in Table 9.6. The root-mean-square error and correlation coefficient arising from comparisons between the predicted and measured reports of "3: Mild nausea" are also given. Figure 9.6 shows the correlation between the predicted and measured reports of "3: Mild nausea" for the conditions investigating the percentage of roll-compensation.

The correlations in Tables 9.4, 9.5 and 9.6 and the graphs in Figures 9.4, 9.5 and 9.6 demonstrate that Equation 5 is capable of predicting the effect of the percentage of roll-compensation observed during the laboratory studies; although, as the model parameters vary greatly between fits, it is unclear whether one set of model parameters can be used to predict motion sickness with these conditions.

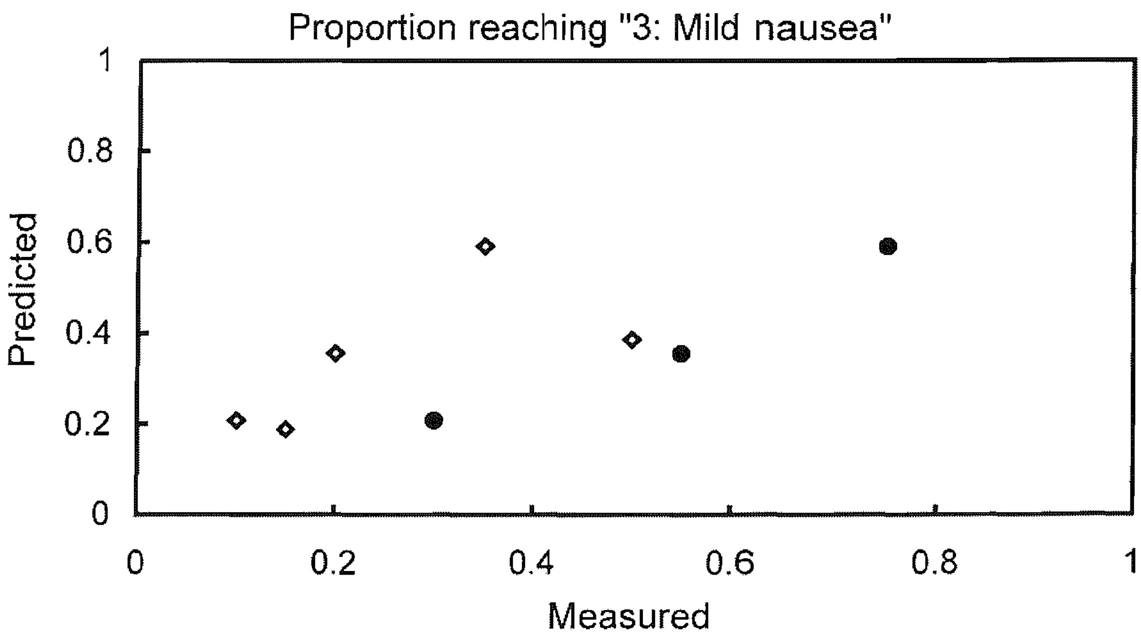

Figure 9.6 Correlation between predicted and measured proportions of subjects reporting "3: Mild nausea" during exposure to various percentages of roll-compensation with 0.2 and 0.1 Hz lateral oscillations. Solid black circles: 0.2 Hz lateral oscillation; Open diamonds: 0.1 lateral oscillation.

Table 9.7 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposure to the combined lateral and roll oscillations reported in this thesis.

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
0.299	-0.471	-0.494	-0.459	0.120	0.761

As expected from functional analysis of the motion sickness model, the best-fit model parameters found with the groups of conditions studying the effect of the percentage of roll-compensation indicate that either the parameter $k_{y,oto}$ or the parameter $k_{y,scc}$ must be negative to predict the observed effects (the model parameters were not constrained during the various optimisation processes); however, if the sensed and expected forces were determined purely from otolith and semi-circular canal sensation then the associated model parameters, $k_{y,oto}$ and $k_{y,scc}$, would not be negative (i.e. with positive parameters, and as originally defined, Equation 5 would be sufficient to predict motion sickness). Thus, the sensed and expected forces may not be easily calculated, as another sensory system may influence their formation. Irrespective of this possibility, the model still provides a suitable mechanism for predicting sickness, as it allows for negative coefficients.

Model parameter fitting for motion sickness with roll-compensated lateral oscillations

The model parameters giving the best fit to the proportions of subjects reporting "3: Mild nausea" during the studies of combined lateral and roll oscillation conducted for the purposes of this thesis (with the motion parameters reported in Tables 6.1, 7.1 and 8.1) are shown in Table 9.7. The root-mean-square error and correlation coefficient arising from comparisons between the predicted and measured reports of "3: Mild nausea" are also given. Figure 9.7 compares the predicted and measured reports of "3: Mild nausea" for each condition in the studies of combined lateral and roll oscillation.

Relative to the errors and correlations obtained when Equation 5 was fitted to data with other groups of conditions, the parameter fit obtained with data from all the conditions studied in this thesis gave the highest correlation and a relatively low root-mean-square error; thus, the model was able to predict simultaneously the reports of "3: Mild nausea" from all the combined lateral and roll oscillation conditions studied for the purposes of this thesis.

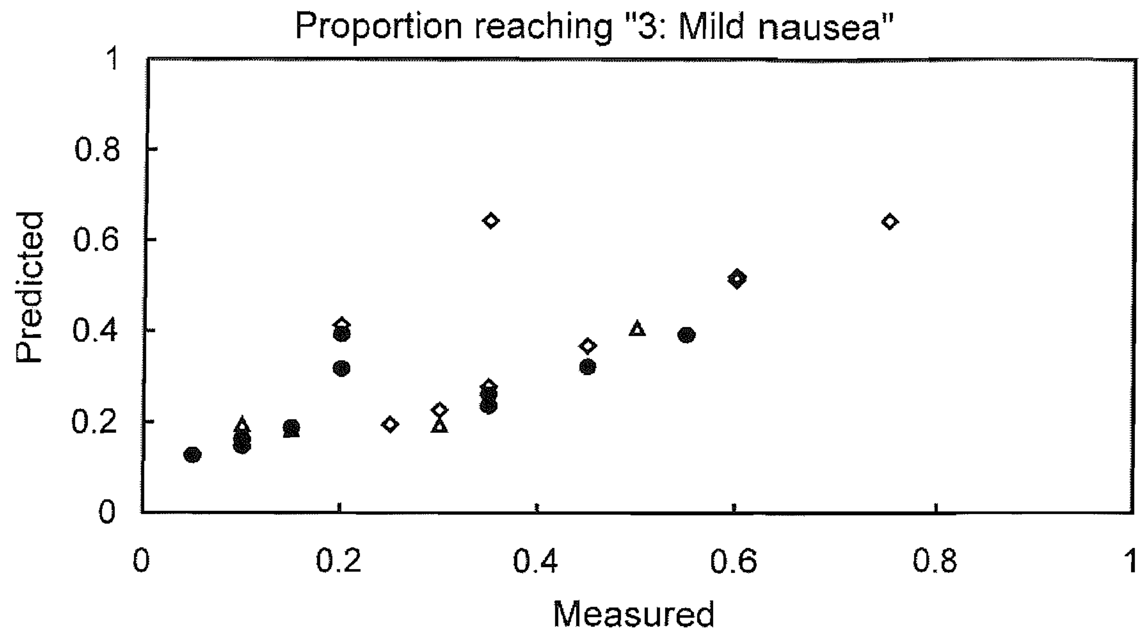

Figure 9.7 Correlation between predicted and measured proportions of subjects reporting "3: Mild nausea" during exposure to the combined lateral and roll oscillations studied for the purposes of this thesis. Solid black circles: uncompensated lateral oscillation; Open diamonds: fully roll-compensated lateral oscillation; Open triangles: intermediate roll-compensated lateral oscillation.

9.3.3 Predictions of motion sickness with pure vertical oscillation

Introduction

The previous section compared and calculated model predictions of motion sickness for the various conditions of combined lateral and roll oscillation investigated in this thesis. As seen in the literature review, a large body of work has investigated motion sickness with pure vertical oscillation. No data pertaining to the proportion of subjects reporting "3: Mild nausea" with various conditions of vertical oscillation were available for analysis for the purposes of this discussion; however, a functional analysis can be completed as the model includes terms dependent on the vertical forces experienced by the subject, and such predictions of motion sickness with pure vertical oscillations are explored here.

Definition of the force environment with pure vertical oscillation

The Earth-referenced motions are:

$$f_y = 0$$
$$f_z = g - a_z$$
$$\varphi = 0$$

As there is no rotation of the subject relative to the Earth, the subject-referenced forces are given as follows:

$$f'_y = 0$$
$$f'_z = g - a_z \qquad \text{Equation 10}$$

Functional analysis of model predictions of motion sickness with pure vertical oscillation

After substitution into Equation 2 of the appropriate subject-referenced forces, given by Equation 10, the form of the model becomes

$$|e| = \left|\left(k_{z,oto} - k_{z,scc}\right) \cdot g - k_{z,oto} \cdot a_z\right| \qquad \text{Equation 11}$$

As the values of g, and the gains $k_{z,oto}$, and $k_{z,scc}$ are assumed constant (for any fit of these parameters to a given data set), Equation 11 predicts that the error or mismatch ($|e|$) with pure vertical oscillation will be linearly dependent on the magnitude of the vertical acceleration in the Earth-vertical direction. This finding is consistent with those reported in the previous studies of vertical oscillation reviewed in Chapter 2; however, further comparisons to measured motion sickness data are necessary to confirm this conclusion.

9.3.4 Predictions of motion sickness with pure roll oscillation

Introduction

Motion sickness with pure roll oscillation was not studied in the series of experiments conducted for this thesis. Data from previous studies of motion sickness with roll oscillation were available within the HFRU (Howarth and Griffin, 2003). The study by Howarth and Griffin (2003) was described in Section 2.10.6 and the motion and sickness data were summarised in Table 2.11. This section describes model predictions of motion sickness with roll oscillation and compares them to the findings of the earlier study.

Definition of force environment with pure roll oscillation

The Earth-referenced motions are given as follows:

$$f_y = 0$$
$$f_z = g$$
$$\varphi = \varphi$$

The subject-referenced forces are given as follows:

$$f'_y = g \cdot \sin\varphi \approx g \cdot \varphi$$
$$f'_z = g \cdot \cos\varphi \approx g \qquad \text{Equation 12}$$

Table 9.8 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposure to pure roll oscillation (Howarth and Griffin, 2003).

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
0.040	0.000	-0.040	0.000	0.037	---

Functional analysis of model predictions for pure roll oscillation

Appropriate substitution of the subject-referenced forces associated with pure roll oscillation (given in Equation 12) into Equation 2 gives the following expression to predict the mismatch or error:

$$|e| = \left[g^2 \cdot \varphi^2 \cdot \left(k_{y,oto} - k_{y,scc}\right)^2 + g^2 \cdot \left(k_{z,oto} - k_{z,scc}\right)^2\right]^{1/2}$$

Which can be simplified using:

$$|e| = g \cdot \left[\left(k_{y,oto} - k_{y,scc}\right)^2 \cdot \varphi^2 + \left(k_{z,oto} - k_{z,scc}\right)^2\right]^{1/2} \qquad \text{Equation 13}$$

The values of g, and the gains $k_{y,oto}$, $k_{y,scc}$, $k_{z,oto}$, and $k_{z,scc}$ are assumed constant and the Equation 13 predicts that motion sickness with pure roll oscillation is dependent on the roll magnitude, φ. The result does not contradict the conclusion from the earlier study (Howarth and Griffin, 2003), which stated that motion sickness with constant peak roll displacements was independent of frequency (and therefore not dependent on either the roll velocity or roll acceleration); however, the effect on motion sickness of the roll magnitude is not known and further research is required.

Quantitative model predictions for pure roll oscillation

The model parameters giving the best fit to the proportions of subjects reporting "3: Mild nausea" during exposure to pure roll oscillation are shown in Table 9.8. The root-mean-square error and correlation coefficient arising from comparisons between the predicted and measured reports of "3: Mild nausea" are also given. Figure 9.8 compares the predicted and measured reports of "3: Mild nausea" for each frequency of roll oscillation.

Figure 9.8 demonstrates that the model can fit to reports of motion sickness with pure roll oscillation. With these conditions the angle of roll did not change and the model predicts equal reports of "3: Mild nausea"; thus, the correlation coefficient is not a valid measure with which to assess the efficacy of the model with these conditions. Of the model fits calculated in this Discussion chapter, the root-mean-square error was the lowest when the model parameters were fitted to the pure roll oscillation data.

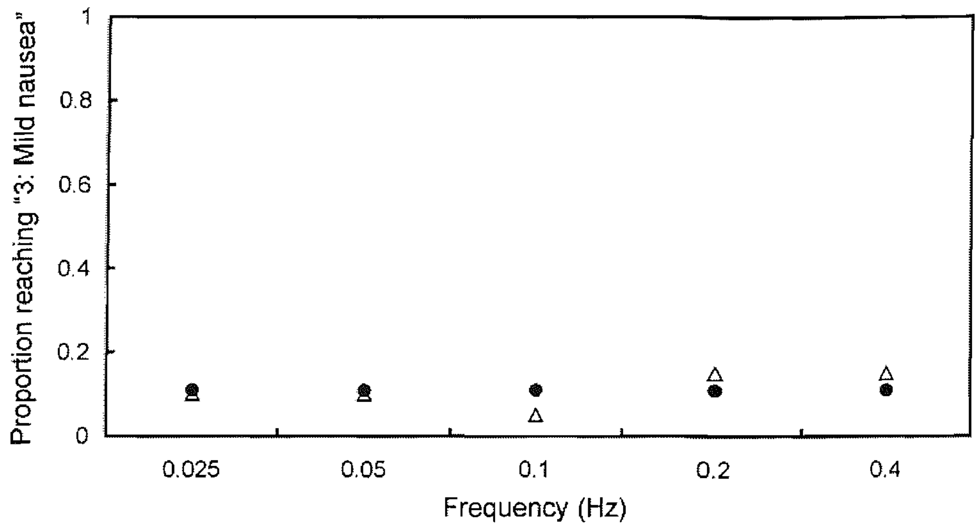

Figure 9.8 Predicted and measured proportions of subjects reporting "3: Mild nausea" during exposure to pure roll oscillation (Howarth and Griffin, 2003). Solid black circles: predicted proportion of subjects reporting "3: Mild nausea"; Open triangles: measured proportion of subjects reporting "3: Mild nausea".

9.3.5 Quantitative model predictions for conditions involving lateral and roll oscillation

The conditions conducted for the purposes of this thesis and the conditions conducted for the study of roll oscillation reported above (data from Howarth and Griffin, 2003) were combined into one group and the mismatch predicted by Equation 2 was fitted to the reports of "3: Mild nausea". The resulting model parameters are shown in Table 9.9. The root-mean-square error and correlation coefficient arising from comparisons between the predicted and measured reports of "3: Mild nausea" are also given. Figure 9.9 shows the correlation of the predicted and measured reports of "3: Mild nausea" for all conditions of pure, or combined, lateral and roll oscillations.

Figure 9.9, shows that when optimised across all conditions, Equation 2 could be fitted to the reports of "3: Mild nausea"; however, the figure shows large variations in correlation between the groups of conditions: e.g. motion sickness with intermediate compensation (when the compensation ratio was in the range $0 < p < 1$) did not show as linear a correlation as motion sickness with uncompensated and fully roll-compensated lateral oscillations ($p = 0$ or $p = 1$).

Table 9.9 Model parameters, root-mean-square error and correlation coefficient for a fit of the model to reports of "3: Mild nausea" during exposures involving pure or combined lateral and roll oscillations.

$k_{y,oto}$	$k_{z,oto}$	$k_{y,scc}$	$k_{z,scc}$	Root-mean-square error	R^2
0.225	2.110	0.226	2.095	0.140	0.662

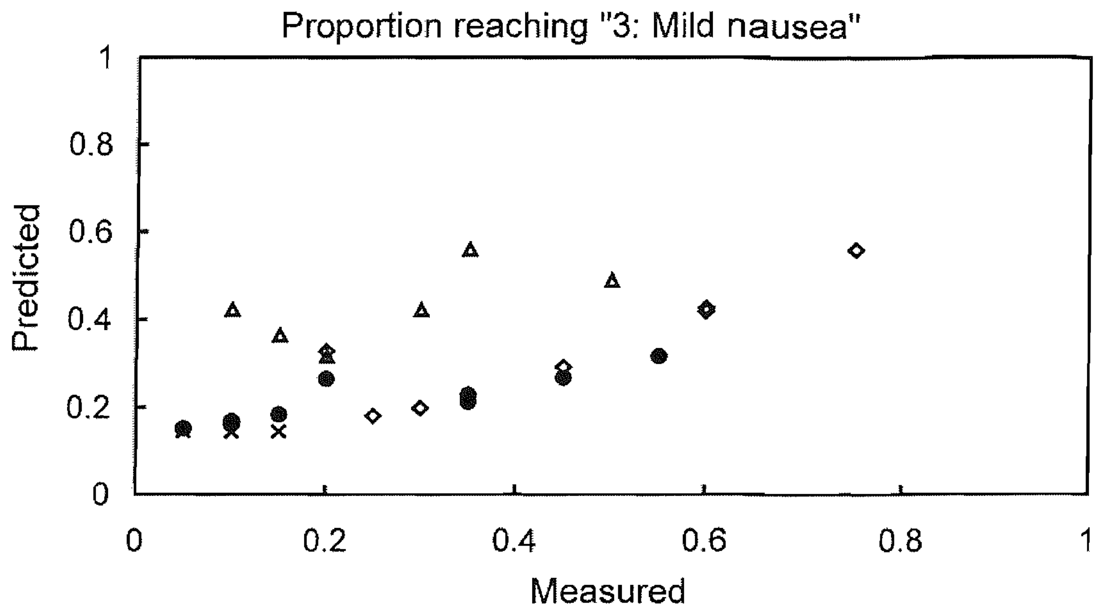

Figure 9.9 Correlation between predicted and measured proportions of subjects reporting "3: Mild nausea" during exposure to pure or combined lateral and roll oscillations. Solid black circles: pure lateral oscillation; Open diamonds: fully roll-compensated lateral oscillation; Open triangles: intermediate roll-compensated lateral oscillation; Crosses: pure roll oscillation.

9.4 DISCUSSION OF FINDINGS

9.4.1 Introduction

This section reviews the findings from the investigations reported in this thesis, placing them in the context of the thesis aims. Findings from the laboratory studies of combined lateral and roll oscillation are first described and the conclusions are briefly compared to those from other studies. The development of the motion sickness model and its strengths and weaknesses are summarised. A critique of the models assumptions, with some suggestions for further development, then follows.

9.4.2 Findings from investigations of lateral and roll oscillations

Stated objectives of the series of investigations of combined lateral and roll oscillation were: to identify the effects of frequency and relative magnitude between the component motions, to study motion sickness with lateral oscillations at frequencies less than 0.2 Hz, and to consider the findings in the context of the application to motion sickness on tilting-trains.

Studies of uncompensated or fully roll-compensated lateral oscillations found significant variations of motion sickness with changing magnitude and frequency of oscillation. In total, four findings were concluded from the laboratory experiments:

i) at low frequencies some similar effects of frequency were found between studies of uncompensated and fully roll-compensated lateral oscillation; i.e.

motion sickness tended to be proportional to acceleration with frequencies up to about 0.315 Hz

ii) an acceleration frequency-weighting calculated for pure lateral oscillations differed from that previously defined for vertical oscillations.

iii) fully roll-compensated lateral oscillations tended to cause more motion sickness than uncompensated lateral oscillations;

iv) motion sickness did not increase linearly with increasing roll-compensation but progressively decreased with increasing roll-compensation up to about 50% and then progressively increased with increasing compensation up to 100%;

v) motion sickness with lateral and roll oscillations cannot be predicted from either one of the Earth-lateral or subject-lateral acceleration, roll displacement or vertical acceleration.

Findings of increased compensation causing increased motion sickness were consistent with previous laboratory studies of combined lateral and roll oscillation, which found increased motion sickness when roll oscillation was added to lateral oscillation (Förstberg, 1999 and Stott *et al.* 2000). That the addition of roll motion to lateral oscillations did not produce linear changes in motion sickness was consistent with hypotheses suggested in previous studies of combined translational and rotational oscillations (Wertheim *et al.*, 1998).

Of the 23 conditions studied, a total of twelve conditions involved combined lateral and roll harmonic oscillations at frequencies less than 0.16 Hz. This number of conditions is approximately six times greater than the number of published conditions reported in the review of literature as having investigated harmonic translational oscillations at frequencies less than 0.16 Hz; one condition was reported with pure fore-and-aft oscillation at 0.1 Hz (Golding *et al.*, 2001) and the other with pure vertical oscillation at 0.083 Hz (McCauley *et al.*, 1976).

In terms of the application to tilting-trains, the conclusions are consistent with reports of motion sickness observed on tilting-trains (Förstberg, 1998 and Förstberg, 2003), where motion sickness increased with increasing roll motion when it was combined with lateral acceleration.

9.4.3 Motion sickness modelling

In summary, a quantitative motion sickness model was developed from two conditions of neural mismatch (Stott, 1986) arising from postulated relationships between vestibular sensation and the expected sensation of motion. The postulates were developed to express quantitative predictions of motion sickness as errors arising from differences between the sensed and expected forces. A mathematical form was attributed to each error; the first hypothesised a direction error and the second hypothesised a magnitude error. Finally, vector analysis was used to combine the hypothesised magnitude and direction errors, such that motion sickness was hypothesised as being proportional to the magnitude of the vector difference between the sensed and expected forces.

The model was simplified in order to predict motion sickness with combined lateral and roll oscillations, where the roll displacements and lateral forces were in phase and the roll displacements act to reduce the lateral forces experienced by subjects. When optimised separately for groups of similar conditions, correlation analysis showed that the model predicted the trends in motion sickness observed during the studies of pure lateral oscillation, fully roll-compensated lateral oscillation and partially roll-compensated lateral oscillation. Furthermore the same model predicted an effect of motion magnitude on motion sickness with pure vertical and pure roll oscillations that did not contradict existing knowledge.

Analysis of the form of the model with each group of conditions showed that for specific types of motion (e.g. either pure lateral oscillations, roll-compensated lateral oscillations or pure roll oscillations) the model predicted the observed trends; however, the sets of optimised parameters varied greatly between fits to the various groups of conditions. With the conditions of combined lateral and roll oscillation investigated in this thesis, the model was able to fit the data and the optimised parameters were consistent with those suggested by functional analysis of the model. When reports of motion sickness with pure roll oscillation were added to those from the laboratory experiments studied here, the model was less well able to fit to the data. Thus, it is likely that a unique set of parameters did not exist for all the model implementations and conditions investigated here.

As several assumptions were necessary to simplify the model to a form suitable for predicting motion sickness with combined lateral and roll oscillation, it is likely they had an effect on the success of the model (e.g. the effects of frequency, vision and duration were not included in the model). Possible influences of the assumptions are explored in the next section and, where possible, appropriate suggestions for future work are made.

9.4.4 Critique of model assumptions

Introduction

A critique of the proposed model is undertaken here by examination of the assumptions used in its formulation.

Predicted mismatch proportional to motion sickness

The motion sickness model was formulated so as to predict the degree of mismatch, or neural mismatch, for any given combined lateral and roll oscillation. The mismatch was represented by an error and the error was compared directly to the proportions of subjects reporting "3: Mild nausea". Thus, it was assumed that the predicted incidence of illness was proportional to the magnitude of the error. One source of error with this assumption is that the proportion of subjects reporting motion sickness within a population can vary only within the range from zero (0%) to one (100%), whereas, it is possible that the model might predict proportions reporting sickness greater than 1. Thus, some care will be required if extrapolating the model to other motion environments.

It is not known how well the model will predict other measures of motion sickness. In the modelling reported here, the proportion of subjects reporting "3: Mild nausea" was chosen, as this was the highest illness rating which was reported in all conditions (i.e. reports of "4: Mild to moderate nausea" were not given in all conditions of combined lateral and roll oscillation) and had been previously suggested as being of practical significance in predicting motion sickness in tilting-trains.

Effect of vision

A fundamental assumption relating to the mechanisms influencing motion sickness concerns the effect of the visual scene, as described by Stott's 1st postulate (Stott, 1986). In the series of experimental studies reported here, the visual scene remained fixed relative to the subject's coordinate system, both in terms of translation and rotation: subjects had no visual cue (or "external view") of their movement relative to an inertial geocentric coordinate system. Thus, it was assumed that the 1st postulate was violated by all experimental conditions and the relative effect of this violation was dependent on the magnitude, frequency and direction of oscillation; however, the interaction causing the subsequent effect was assumed invariant throughout the motion conditions.

Typically, the effect of the visual scene is assumed only to moderate motion sickness (Griffin, 1990); however, an alternative and unspecified effect of vision may have been responsible for the changes in sign of the model parameters, when they were optimised to predict the observed effects of adding roll to lateral oscillation. The findings suggest that estimates of the sensed or expected forces may not be formed purely from otolith or semi-circular canal information but require other information and processes; e.g. from the visual system.

Effect of phase

In the studies reported in this thesis the Earth-lateral forces and roll displacements were in phase and, in the initial implementation of the model, there were no mechanisms to account for any possible effects of phase. Prior to the experimental investigations, it was assumed that the effect of relative phase between lateral and roll displacements was less important than the effect of relative magnitude such that, when the former was fixed, studies of the latter would provide sufficient information to predict motion sickness in tilting-trains.

A practical application of studying combined lateral and roll oscillations is the possibility to find combinations that will minimise motion sickness in tilting-trains. It has been found that motion sickness can be minimised by judicious selection of the relative magnitudes of lateral and roll oscillation; however, it may be possible that phase leads and lags between lateral and roll motions (with equivalent relative lateral and roll magnitudes) might produce changes in sickness (it is known that the organs responsible for motion sensation have differing magnitude and phase responses); thus, motion sickness in tilting-trains might alternatively be minimised by appropriate selection of the relative phase between lateral and roll motions.

In order to incorporate phase information in to the proposed model, the model parameters ($k_{y,oto}$, $k_{y,scc}$, $k_{z,oto}$, and $k_{z,scc}$) may require time lags (e.g. an exponential function with an appropriate time constant) to be associated with them. A rationale and methodology for a laboratory experiment to investigate the influence of the effect of phase is described in further detail in the next chapter.

Effect of frequency

Other than assuming that motion sickness was caused by oscillations at frequencies less than 1.0 Hz, the model did not assume any frequency dependence on motion sickness. A review of literature and the studies conducted for the purposes of this thesis provided strong evidence that there is a significant effect of frequency on motion sickness and that a complete model will need to consider this factor.

When considering motions in one axis, previous models anticipated that motion sickness was a function of the acceleration magnitude in the axis of motion. Subsequently, acceleration frequency-weightings were calculated by normalising the motion sickness reported at some frequency of oscillation with the acceleration magnitude. Within this thesis, earlier discussions about the effects of frequency observed in each of the laboratory experiments found that there was no one common motion variable or weighting that that would predict motion sickness for lateral, vertical or combined lateral and roll oscillations; however, later modelling work proposed that motion sickness with these motions increased as the gravito-inertial force increased. Therefore, it is suggested that the susceptibility to motion sickness as a function of frequency may be better predicted by normalising reports of motion sickness with the gravito-inertial force magnitude.

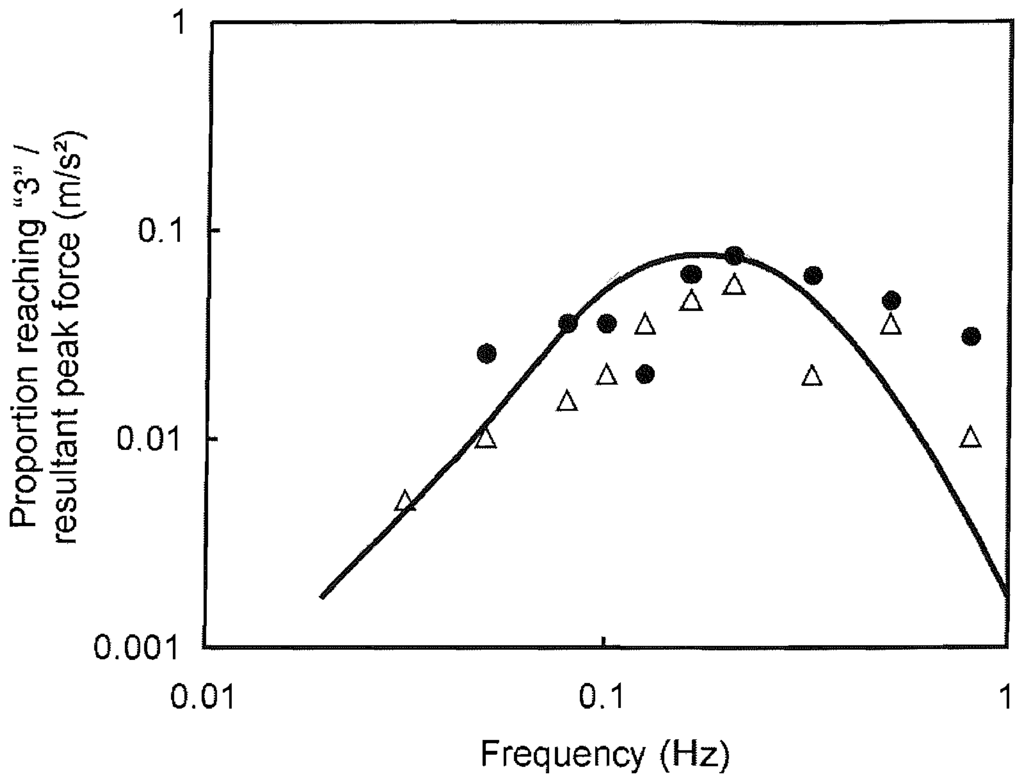

Figure 9.10 Frequency-weightings calculated from the studies of pure lateral oscillation and 100% roll-compensated lateral oscillation, where the reports of "3: Mild nausea" were normalised by the gravito-inertial force experienced at each frequency of lateral oscillation. Solid black circles: weightings calculated for fully roll-compensated; Open triangles: weightings calculated for pure lateral oscillation.

Figure 9.10 presents the weightings calculated for the laboratory studies involving the ten conditions of pure lateral oscillation and the nine conditions of 100% roll-compensated lateral oscillation (with the motion parameters tabulated in Tables 6.1, 7.1, and 8.1, and the reports of "3: Mild nausea" detailed in Chapters 6, 7, and 8), where the reports of "3: Mild nausea" were normalised by the gravito-inertial force experienced by subjects in each motion condition. The weightings are compared to the realisable acceleration frequency-weighting defined for vertical oscillation. Two findings were observed.

i) The weightings predict a similar dependence on frequency for each type of motion.

ii) Motion sickness with 0.1 Hz oscillation no longer seems to give contrasting results to those at other frequencies.

The frequency-weighting in Figure 9.10 bears comparison to the effect of fore-and-aft oscillation frequency observed by Golding *et al.* (Golding and Markey, 1996; Golding, *et al.*, 1997; Golding, *et al.*, 2001), which was reported in Chapter 2 and illustrated in Figure 2.35; with these studies, each set of experimental conditions had constant peak acceleration magnitudes and therefore constant peak gravito-inertial force magnitudes.

Practically, some work may be required to implement a 'gravito-inertial force frequency weighting', although it is anticipated that the weighting may be used in conjunction with the proposed model: one possibility is that the parameters within the model ($k_{y,oto}$, $k_{y,scc}$, $k_{z,oto}$, and $k_{z,scc}$) are frequency-dependent and another possibility is that frequency weighting might occur after calculation of the conflict error.

Effect of duration and habituation

The proposed model predicted the proportion of subjects to have reported "3: Mild nausea" by the end of a 30-minute exposure to motion, it did not predict at what instant subjects might have reported "3: Mild nausea". As all experiments were of the same duration, it was assumed that the duration of exposure had no influence on the relative proportions of subjects reporting motion sickness at any given instance in time (c.f. the proportional hazards assumption used in Cox regression).

Previous models have used mathematical constructs such as Hill transforms and 'leaky integrators' (e.g. Oman, 1982; Bos and Bles, 1998) to model the development of the symptoms of motion sickness. Further modelling work may be beneficial in order to incorporate predictions of the time course of symptoms within the proposed model.

Two factors that are known to influence the development of symptoms are habituation and adaptation to a motion environment. Prior to the start of the motion exposure, subjects were assumed to be adapted and habituated to a 'normal' terrestrial force environment: i.e. an inertial geocentric system. As naïve subjects were exposed to combined lateral and roll oscillations for a period of 30-minutes, it was assumed that they did not adapt or habituate over this time.

Future implementations of the model may include terms to predict the time course of habituation. Again, it is suggested that the model parameters, and in particular the $k_{y,scc}$ and $k_{z,scc}$ terms (which were hypothesised to relate to the expected sensations of force), may be made time-dependent; these parameters might be modified by internal models using feedback to adjust the expected force sensations.

Effect of centre of roll

In tilting-trains the axis about which passengers roll is usually found at the seat surface. For this practical reason, the centre of roll was located at the seat surface in the laboratory experiments. As the head was in the order of 1 metre from the centre of roll, and as the frequencies of oscillation were less than 1.0 Hz, such that the angular velocities were low, the modelling assumed that the radial and tangential forces arising from translation of the head were negligible.

Future laboratory studies and modelling work may be required to determine the influence of the centre of roll on motion sickness with combined translational and rotational motions.

A laboratory experiment to investigate the influence of the centre of roll is described in further detail in the next chapter.

Effect of posture

It was assumed that for the majority of most journeys in tilting-trains, most passengers would remain seated. So for practical purposes, only seated subjects were tested in the experimental work. The subjects sat upright, with a low backrest, and, with low frequencies of oscillation, were assumed to act as a rigid body, such that there was no influence of posture. Barring small reflexive movements or postural adjustments, the subjects also were assumed passive, such that they did not contribute to their motion exposure and their subsequent motion sickness. Little is known about the effect of posture on motion sickness. Studies of translational oscillation with extreme variations of posture, ranging between seated upright and lying supine, found significant differences in motion sickness (Golding and Kerguelen, 1992; Golding *et al.*, 1995). Further fundamental studies of the effect of posture on motion sickness are required.

Force and motion sensation

Stott's postulates (Stott, 1986) were explicitly described in terms of visual and vestibular interactions. The subsequent model developed in this discussion assumed that the otolith and semi-circular canals were the sensory systems primarily responsible for motion sickness.

It is likely that more than one sensory system is responsible for the estimation of the sensed and expected forces. For example, the sensed force may be a composite estimate reflecting either the best estimate derived from several peripheral sources (i.e. directly from sensory afferent information), or the best central estimate, derived from internal models, either with or without sensory weighting mechanisms for combining sensory afferent information (e.g. Merfeld, 2002). Further work is necessary to determine the processes by which such estimates are derived (e.g. whether or how the sensory information is integrated or processed by peripheral or central sensory nervous systems) and whether the systems known to be responsible for controlling visual and ocular interactions might also be responsible for or related to motion sickness.

A generalised motion sickness model

Further consideration of the origin of the estimates of the sensed and expected forces leads to a generalisation of the proposed motion sickness model. As it is unclear what sensory systems are responsible for estimates of the sensory and expected forces, it is suggested that the terms in the model may be better off denoted using less specific subscripts. The model may be re-written to distinguish only between the estimates of the sensed and expected force vectors, denoted $\mathbf{f}_{sens}$ and $\mathbf{f}_{exp}$ respectively:

$$\mathbf{e} = \mathbf{f}_{sens} - \mathbf{f}_{exp}$$

$$\begin{bmatrix} e_y \\ e_z \end{bmatrix} = \begin{bmatrix} f_{y,sens} \\ f_{z,sens} \end{bmatrix} - \begin{bmatrix} f_{y,exp} \\ f_{z,exp} \end{bmatrix}$$

The generalised expression predicting the magnitude of the error is given by

$$|\mathbf{e}| = \left[\left(f_{y,sens} - f_{y,exp} \right)^2 + \left(f_{z,sens} - f_{z,exp} \right)^2 \right]^{1/2}$$

A 3-dimensional motion sickness model

The model developed to predict motion sickness with combined lateral and roll oscillation required consideration of forces in only two axes, the subject-lateral and subject-vertical forces, and the roll displacement. The model was thought suitable for the application to predicting motion sickness in the tilting-train environment; however, to predict motion sickness in other force environments, as might be encountered on other modes of transport, a 3-dimensional model is required. One possible extrapolation of the proposed model is described here.

In the proposed model, the expected force was that due to gravity and it changed with changing orientation with respect to the Earth caused by changing roll displacements. As explained in Appendix A, roll displacements are non-commutative and a 3-dimensional model of motion sickness will require estimates of the gravity force vector to be determined from integrated roll velocity information. Thus, in a 3 dimensional force environment the expected force, $\mathbf{f}_{exp}$ is given by

$$\mathbf{f}_{exp} = -\int \boldsymbol{\omega}_{exp} \wedge \mathbf{f}_{exp}$$

where $\boldsymbol{\omega}_{exp}$ is the estimated three-dimensional roll velocity vector and the initial conditions for the expected force are typically given by:

$$\mathbf{f}_{exp} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

Therefore, the expected force can be hypothesised to have a form similar or equivalent to

$$\mathbf{g} = -\int \boldsymbol{\omega} \wedge \mathbf{g}$$

If the sensed force in the subject-referenced coordinate system is given by $\mathbf{f}_{sens}$, then the 3-dimensional conflict error predicted by the mismatch model will be given by

$$\mathbf{e} = \mathbf{f}_{sens} - \int \boldsymbol{\omega}_{exp} \wedge \mathbf{f}_{exp}$$

The magnitude of the error can be calculated in the previously hypothesised manner using the root-sum-of-squares of the error vector component magnitudes. Further fundamental laboratory and modelling work are necessary to test the hypothesised model.

9.4.5 Application of model to space motion sickness

The proposed model is suggested as being congruent with the hypothesised otolith tilt-translation re-interpretation hypothesis developed to predict space motion sickness (Parker *et al.*, 1985; Reschke and Parker, 1987); although further work is necessary to adapt the model for this environment. On the introduction of a subject to the space environment, the expected forces arising from the force due to gravity are absent and so motion sensation and expectation differ and the model might be used to predict sickness; however, experimental studies show that expectations of motion change after habituation to the space environment, such that rotations in the head are no longer expected to correspond to changes in force arising from changes in orientation with respect to gravity. A practical implementation of the model to fit this data would require the model parameters related to the expectation of motion to equal zero. In this instance it then would be expected that any low frequency translational accelerations would then be responsible for any subsequent sickness.

9.4.6 Practical application of findings

Studies of actual tilting-train motions found that, relative to the Earth-lateral forces, typical percentages of roll-compensation offered by tilting-trains were in the region of 42% to 86%, where a percentage compensation of 42% occurred when the tilt mechanism was inoperative (see Chapter 3). Laboratory studies of roll-compensated lateral oscillation found that motion sickness tended to be a minimum when the compensations were in the region of 50% and tended to increase with increasing compensation up to 100%. The findings suggest that conventional trains operating without tilt offer close to optimum conditions of roll-compensation (i.e. about 40% roll-compensation) in terms of minimising the nauseogenic potential of the Earth-lateral forces. Thus, in the tilting-train environment, motion sickness will increase with increasing tilt-compensation and it is suggested that some other scheme or mechanism (e.g. using an alternative tilt delay or an alternative centre of roll) may be required to reduce motion sickness on tilting-trains; although care must taken when generalising these results as it is likely that any effect on motion sickness, including that of roll-compensation, is likely convolved with the effect of frequency.

9.5 SUMMARY AND CONCLUSIONS

A quantitative motion sickness model based on the concept of neural mismatch was derived. Motion sickness was hypothesised as being proportional to the magnitude of the vector difference between the sensed and expected forces, where the expected force was hypothesised as that due to the force due to gravity. The model was used to predict reports of motion sickness for various combinations of lateral and roll oscillation. Functional analysis of the model suggested that the model was able to predict the changes in motion sickness observed in the laboratory experiments: e.g. that fully roll-compensated lateral oscillation can cause more motion sickness than pure lateral oscillation, but that motion sickness does not increase linearly with increasing roll-compensation. For groups of laboratory experimental conditions involving the same types of motion (e.g. pure lateral or roll-compensated lateral oscillations), sets of parameters were found that were able to fit the model to the data; however, a unique set of parameters, which could fit the model to the data within all groups of conditions (e.g. with pure lateral oscillations, roll-compensated lateral oscillations and pure roll oscillations),was not found.

A review of the assumptions revealed that further work is necessary to develop the model and, where appropriate, suggestions were made. In particular, the known effects of frequency must be determined and the role of the total gravito-inertial force, as opposed to the inertial force (or acceleration), clarified, such that they can be incorporated into the model. It is also suggested that the role of other sensory systems, e.g. the visual system, needs to be considered.

The findings are hoped to have a practical application to the tilting-train environment, where roll motions are used to reduce the lateral forces felt by passengers. The studies suggest that an increase in tilt-compensation will only increase motion sickness, as conventional trains may already operate close to the optimal compensation conditions due the roll provided by the cant of the track. Other compensatory schemes or mechanisms may be required to reduce sickness on a tilting-train; the following chapter describes experiments to investigate two possible mechanisms (e.g. the use of an alternative tilt delay or centre of roll).

CHAPTER 10 FUTURE WORK

10.1 INTRODUCTION

A model for predicting motion sickness with combined lateral and roll oscillation was proposed in the discussion chapter. A necessary critique of the model assumptions provided cues towards areas of possible future research. A brief summary of suggestions is provided here followed by more detailed descriptions of two possible experiments having a practical application to motion sickness on tilting-trains.

10.2 SUGGESTIONS FOR FUTURE RESEARCH

10.2.1 Introduction

Suggestions for future research are stated briefly in this section and, where possible, a short description of how the proposed model might be tested and improved is included.

10.2.2 Predictions of other measures of motion sickness

The model proposed in this thesis was developed to predict the proportion of subjects reporting "3: Mild nausea" during their 30-minute exposure to motion. Previous models have been developed to predict the vomiting incidence within a population exposed to vertical motion (e.g. McCauley *et al.*, 1976; Lawther and Griffin, 1987; and Bos and Bles, 1998). In practice the choice and suitability of any motion sickness measure for any given situation is dependent on the motion environment and the expectations of motion sickness associated with that environment (including what degree of illness is perceived as acceptable). Therefore, it is likely that the model will need to be able to predict other measures of motion sickness, so as to be useful for other environments. Future investigations could observe how the model parameters must change to fit other measures of motion sickness with other data and whether or not other parameters or gains must be included in the model.

10.2.3 Visual scene

Sensations and expectation of motion included in the model were based on the force felt by the subject and the force due to gravity. The sensations, expectations and their interaction were assumed to be invariant with time. As such it was anticipated that only one set of model parameters would be necessary to predict motion sickness with lateral and roll oscillations. As the model parameters changed with changing motion types it can be assumed that the present form of the sensation and/or expectation is insufficient, such that other factors may need to be considered. It is suggested here that the next development step of the model should consider the effect of vision. A systematic investigation of how the model parameters change when fitted to motions similar to those studied here but with changing visual scenes may yield sufficient information to determine the effect of vision on motion sickness.

10.2.4 Relative phase between lateral and roll oscillations

The lateral and roll oscillations examined in this thesis had a constant phase relationship. It is suggested that the effect on motion sickness of the relative phase between the motions is examined, so as to observe whether phase leads or lags reduce motion sickness. A detailed description of a suitable experiment is described later in this chapter.

10.2.5 Effect of frequency

No effect of frequency was assumed within the model. Analysis in the discussion has suggested that a common weighting may exist for compensated and uncompensated lateral oscillations and also for vertical oscillations; i.e. when considering the resultant force acting on the subject rather than the acceleration in the direction of the stimulus. A hypothesis of a singular effect of frequency on motion sickness requires further investigation. The model may incorporate an effect of frequency by making the model parameters frequency dependent. Furthermore, the choice of parameters may be considered within the context of sensory dynamics, such as the dynamic response of the semi-circular canals and otoliths. Alternatively, some other mathematical construct external to the current model may be required to predict the effect of frequency.

10.2.6 Effect of duration and habituation

It is unlikely that the existing variables and parameters in the model can be used to predict the effect of duration. Previous attempts to model the time course of symptoms have used a time-integral function of either the weighted acceleration in the direction of the stimulus (e.g. Lawther and Griffin, 1987) or the conflict (e.g. Bos and Bles, 1998). A similar approach is suggested here.

An effect of habituation may be predicted by the current model by having time-dependent model parameters such that the expectation, and possibly also the sensation of motion (e.g. with changes in subject physiology rather than changes in motion environment), can change as a function of time.

10.2.7 Effect of centre of roll

The centre of roll in the conditions investigated in this thesis was at the centre of the seat surface. It is suggested that the effect on motion sickness of the centre of roll is examined, so as to observe whether motion sickness can be reduced with an appropriate centre of roll. A more detail description of how this might be achieved is described later in this chapter.

10.2.8 Effect of posture

The current model has been defined for lateral and roll oscillations, where both the roll of a subject and the orientation of the resultant force relative to a subject have small angles. Previous studies have found that the effect of posture and orientation of the subject (e.g. seated, standing or supine) can have a significant effect on motion sickness when large changes in angle are used. Further tests of the model are required to find whether or how the model might predict the effect of posture.

10.2.9 Motion sensation and development of generalised model

The modelling work in this thesis has suggested that motion sickness can be quantitatively predicted when the sensation and expectation of motion are adequately defined: the model suggests how the sensation and expectation might be compared and the resulting degree of mismatch calculated. The model does not explicitly describe the origin or calculation of the sensations and expectations of motion, which are likely to be determined from several peripheral and central sensory processes. It is suggested that future research might determine how estimates of sensation and expectation are formed.

10.2.10 Three-dimensional model

A three-dimensional model is essential to predict motion sickness in complex motion environments (e.g. in an aeronautical environment). It is suggested that the model is first tested using data from experiments involving uni-axial motion and then with data from experiments involving multi-axial motions, such that as more data becomes available it can be developed to a full three-dimensional model.

10.2.11 Summary

Several areas for future research have been proposed; however, two areas have a significant practical application in that they may offer alternative methods by which motion sickness can be minimised on a tilting-train. A methodology for two such fundamental investigations of combined lateral and roll oscillations is defined in the following sections.

10.3 EFFECT OF PHASE

10.3.1 Introduction

With the combined lateral and roll motions studied in this thesis, the Earth-lateral forces and roll displacements were in phase; however, engineering constraints dictate that the Earth-lateral forces and roll displacements to which passengers are exposed in tilting-trains cannot always be in phase. On a tilting-train, the relative phase between the lateral and roll motions will affect the overall degree of compensation experienced by passengers; i.e. the overall compensation is a function of both the relative phase and relative magnitude of the lateral and roll motions.

An expression describing the effect of the relative phase on the overall compensation experienced by subjects is developed here and the model is used to predict the variation in the error, or conflict, as a function of the relative phase.

10.3.2 Review of lateral and roll relationships studied in the previous experiments

As a function of time, the lateral force felt by a subject, $f_y'(t)$, whilst undergoing combined lateral and roll oscillation with Earth-lateral forces, $f_y(t)$, and roll displacements of the subject about the Earth-referenced x-axis, $\varphi(t)$, is given by:

$$f_y'(t) = f_y(t) + g \cdot \varphi(t)$$

Previous studies in this thesis investigated 100% roll-compensated lateral oscillation, where the subject-referenced lateral forces, $f_y'(t)$, were zero, due to the Earth-lateral forces and roll displacements being in phase. The roll-displacement required to satisfy this condition for a given lateral force $f_y(t)$ was given by

$$\varphi(t) = -\frac{f_y(t)}{g}$$

Assuming harmonic Earth-lateral oscillation of amplitude f_{y0}, such that

$$f_y(t) = f_{y0} \cdot \sin \omega t \,,$$

then the roll displacement magnitude required for 100% roll compensation was

$$\varphi(t) = -\frac{f_{y0} \cdot \sin \omega t}{g}$$

10.3.3 Relationship between relative phase and compensation

A future experiment investigating the effect of phase might use Earth-lateral forces and roll displacements with the same amplitudes as those used in the studies of 100% roll-compensated lateral oscillation reported in this thesis. If the Earth-lateral force and roll displacements are out of phase by a factor, θ, then the Earth-lateral force is written as:

$$f_y(t) = f_{y0} \cdot \sin(\omega t + \theta)$$

An expression describing the resultant subject-referenced lateral force is obtained by appropriate substitution of the Earth-lateral force and roll displacement:

$$f_y'(t) = f_{y0} \cdot \sin(\omega t + \theta) - g \cdot \frac{f_{y0} \cdot \sin \omega t}{g}$$

The equation simplifies to become

$$f_y'(t) = f_{y0} \cdot \{\sin(\omega t + \theta) - \sin \omega t\}$$

The expression can be simplified further using the following trigonometric identity:

$$\sin \alpha - \sin \beta = 2 \cdot \sin\left(\frac{\alpha - \beta}{2}\right) \cdot \cos\left(\frac{\alpha + \beta}{2}\right)$$

Therefore if $\alpha = \omega t + \theta$ and $\beta = \omega t$

$$f_y'(t) = f_{y0} \cdot \{\sin(\omega t + \theta) - \sin \omega t\}$$
$$f_y'(t) = 2 \cdot f_{y0} \cdot \sin\left(\frac{\theta}{2}\right) \cdot \cos\left(\omega t + \frac{\theta}{2}\right)$$

The expression shows that the subject-referenced lateral force varies as a co-sinusoidal function of time:

$$f_y'(t) = f_{y0}' \cdot \cos\left(\omega t + \frac{\theta}{2}\right)$$

where the amplitude, f_{y0}', is dependent on the Earth-lateral oscillation magnitude, f_{y0}, and the relative phase between the roll displacement and the Earth-lateral force, θ:

$$f_{y0}' = 2 \cdot f_{y0} \cdot \sin\left(\frac{\theta}{2}\right)$$

The cosine describing the variation in Earth-lateral force with time is an even function; however, the subject-lateral oscillation amplitude is described by an odd function of the relative phase between the lateral and roll oscillations. Thus, leads or lags of the same angle (but opposite signs) result in subject-lateral forces with the same amplitude, but opposite signs.

By assuming that the desired subject-lateral force amplitude is a proportion of the Earth-lateral force (albeit shifted in phase), as determined by the desired overall compensation ratio, p, it is seen that:

$$f'_{y0} = f_{y0} \cdot (1-p)$$
$$f'_{y0} = 2 \cdot f_{y0} \cdot \sin\left(\frac{\theta}{2}\right)$$

Hence

$$f_{y0} \cdot (1-p) = 2 \cdot f_{y0} \cdot \sin\left(\frac{\theta}{2}\right)$$

The overall compensation ratio, p, for a given relative phase, θ, between the Earth-lateral force and roll displacement is:

$$p = \frac{f_{y0} - 2 \cdot f_{y0} \cdot \sin\frac{\theta}{2}}{f_{y0}}$$
$$p = 1 - 2 \cdot \sin\frac{\theta}{2}$$

Similarly, the expression can be re-arranged to give the phase required for a desired overall compensation ratio:

$$\theta = 2 \cdot \arcsin\left(\frac{1-p}{2}\right)$$

The latter two expressions can be used to form motion conditions with which to test whether motion sickness is dependent on the relative phase of combined lateral and roll oscillations. For example, when the modulus of the phase angles are equal, such that the amplitude of the subject-referenced lateral forces are equal, does a phase lag produce the same motion sickness as a phase lead?

10.3.4 Model predictions of the effect of phase

Model predictions of motion sickness can be obtained for the motions described above (i.e. with lateral and roll amplitudes chosen such that the subject-lateral forces are zero when the Earth-lateral force and roll displacements are in phase).

The subject-lateral force is given by:

$$f'_y(t) = f_{y0} \cdot \{\sin(\omega t + \theta) - \sin \omega t\};$$

and the roll displacements are given by

$$\varphi(t) = -\frac{f_{y0} \cdot \sin \omega t}{g}$$

As the subject-vertical force, f'_z, is approximately constant and equal to g, then the model predicts

$$|e| = \left[f_{y0} \cdot \left(k_{y,oto} \cdot \sin(\omega t + \theta) + \left(k_{y,scc} - k_{y,oto} \right) \cdot \sin \omega t \right)^2 + g \cdot \left(k_{z,oto} - k_{scc} \right)^2 \right]^{1/2}$$

Thus, the effect of phase predicted by the model will depend on the relative values of the two model parameters, $k_{y,oto}$ and $k_{y,scc}$. Note that the model predicts similar motion sickness for fully roll compensated lateral oscillations (θ = 0°) and for lateral oscillations in which the roll motion has the opposite phase (θ = 180°).

10.3.5 Discussion

Investigations of the effect of phase could have a useful practical application; if there were differences between phase leads and lags, tilting-trains could be designed to reduce the lateral forces by keeping the overall compensation high, but minimising sickness by controlling the relative phase of the lateral and roll motions.

As part of such an investigation, studies of the lateral forces and roll displacements measured on tilting-trains would be required to determine the typical relative phase relationships encountered on tilting-trains. Knowledge of the effect of phase gathered from laboratory and field studies would then need to be adapted and incorporated into tilt-control systems.

10.4 EFFECT OF CENTRE OF ROLL

10.4.1 Introduction

Passengers exposed to combined lateral and roll oscillations on a tilting-train tend to be rotated about a roll axis approximately located at the level of the seat surface. Points at a distance from the centre of roll, but rotating with the roll motion, undergo translational motion that can lead to inertial forces at these locations. In the experiments and modelling work conducted for this thesis, only the forces at the seat surface, and not the forces at the head, were considered (the tangential and radial forces at the head were assumed negligible).

It is possible that a passenger's sensation of combined lateral and roll oscillation might vary depending on the location of the centre of roll due to: (i) the change in force imparted to different regions of the body, and (ii) to the distribution and nature of the motion and force sensory systems within the body. Thus motion sickness might vary with changing centre of roll for a given roll-compensated lateral oscillation. If motion sickness changed with varying centre of roll then the finding might provide another mechanism by which motion sickness on tilting-trains can be minimised: a change in the location of the centre of roll within a tilting-train may reduce the chances of motion sickness being reported by subjects.

10.4.2 Proof relating roll displacements to changes in the subject-referenced forces

In the experiments of roll-compensated lateral oscillation conducted for the purposes of this thesis subjects were sat on a chair with the centre of roll through the middle of its surface; however, the centre of roll may be at another location and the initial location at which motion sickness is to be predicted is assumed to be a point located at a distance, r, directly above the centre of roll.

The displacement of point of interest (in the Earth-coordinate frame) due to a rotation through an angle, φ, as a function of time, is given by:

$$d_y = -r \cdot \sin\varphi$$
$$d_z = -r \cdot (1 - \cos\varphi)$$

The velocity of the point (in the Earth-coordinate frame) due to a rotation through an angle, φ, is given by:

$$\dot{d}_y = -r \cdot \dot{\varphi} \cdot \cos\varphi$$
$$\dot{d}_z = -r \cdot \dot{\varphi} \cdot \sin\varphi$$

The acceleration of the point (in the Earth-coordinate frame) due to a rotation through an angle, φ, is given by:

$$\ddot{d}_y = -r \cdot \ddot{\varphi} \cdot \cos\varphi + r \cdot \dot{\varphi}^2 \cdot \sin\varphi$$
$$\ddot{d}_z = -r \cdot \ddot{\varphi} \cdot \sin\varphi - r \cdot \dot{\varphi}^2 \cdot \cos\varphi$$

The acceleration of the point (in the subject-coordinate frame) due to a rotation through an angle, φ, is given by:

$$\begin{bmatrix} \ddot{d}'_y \\ \ddot{d}'_z \end{bmatrix} = -r \cdot \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} \ddot{d}_y \\ \ddot{d}_z \end{bmatrix}$$
$$\begin{bmatrix} \ddot{d}'_y \\ \ddot{d}'_z \end{bmatrix} = -r \cdot \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} \ddot{\varphi} \cdot \cos\varphi - \dot{\varphi}^2 \cdot \sin\varphi \\ \ddot{\varphi} \cdot \sin\varphi + \dot{\varphi}^2 \cdot \cos\varphi \end{bmatrix}$$

The equations for the lateral and vertical acceleration at the point of interest can be re-arranged as follows:

$$\ddot{d}'_y = -r \cdot \left[\cos\varphi \cdot \left(\ddot{\varphi} \cdot \cos\varphi - \dot{\varphi}^2 \cdot \sin\varphi\right) + \sin\varphi \cdot \left(\ddot{\varphi} \cdot \sin\varphi + \dot{\varphi}^2 \cdot \cos\varphi\right)\right]$$
$$\ddot{d}'_z = -r \cdot \left[-\sin\varphi \cdot \left(\ddot{\varphi} \cdot \cos\varphi - \dot{\varphi}^2 \cdot \sin\varphi\right) + \cos\varphi \cdot \left(\ddot{\varphi} \cdot \sin\varphi + \dot{\varphi}^2 \cdot \cos\varphi\right)\right]$$

$$\ddot{d}'_y = -r \cdot \left[\ddot{\varphi} \cdot \cos^2\varphi - \dot{\varphi}^2 \cdot \sin\varphi \cdot \cos\varphi + \ddot{\varphi} \cdot \sin^2\varphi + \dot{\varphi}^2 \cdot \sin\varphi\cos\varphi\right]$$
$$\ddot{d}'_z = -r \cdot \left[-\ddot{\varphi} \cdot \sin\varphi \cdot \cos\varphi + \dot{\varphi}^2 \cdot \sin^2\varphi + \ddot{\varphi} \cdot \sin\varphi \cdot \cos\varphi + \dot{\varphi}^2 \cdot \cos^2\varphi\right]$$

$$\ddot{d}'_y = -r \cdot \left[\ddot{\varphi} \cdot \left(\sin^2 \varphi + \cos^2 \varphi\right) + \dot{\varphi}^2 \cdot \left(\sin \varphi \cdot \cos \varphi - \sin \varphi \cdot \cos \varphi\right)\right]$$
$$\ddot{d}'_z = -r \cdot \left[\ddot{\varphi} \cdot \left(\sin \varphi \cdot \cos \varphi - \sin \varphi \cdot \cos \varphi\right) + \dot{\varphi}^2 \cdot \left(\sin^2 \varphi + \cos^2 \varphi\right)\right]$$

$$\ddot{d}'_y = -r \cdot \left[\ddot{\varphi} \cdot (1) + \dot{\varphi}^2 \cdot (0)\right]$$
$$\ddot{d}'_z = -r \cdot \left[\ddot{\varphi} \cdot (0) + \dot{\varphi}^2 \cdot (1)\right]$$

The equations therefore yield expressions for the tangential and radial accelerations experienced at the point of interest when it is undergoing rotation:

$$\ddot{d}'_y = -r \cdot \ddot{\varphi}$$
$$\ddot{d}'_z = -r \cdot \dot{\varphi}^2$$

When rotating as a function of time, the tangential and radial inertial forces at the location of interest are given by:

$$f'_y = r \cdot \ddot{\varphi}$$
$$f'_z = r \cdot \dot{\varphi}^2$$

When undergoing combined lateral and roll oscillation, the forces at the point of interest in the rotated coordinate system are given by:

$$f'_y = f_y \cdot \cos \varphi + f_z \cdot \sin \varphi + r \cdot \ddot{\varphi}$$
$$f'_z = -f_y \cdot \sin \varphi + f_z \cdot \cos \varphi + r \cdot \dot{\varphi}^2$$

10.4.3 Model predictions of the effect of centre of roll

These forces can be substituted into the model to investigate whether the forces felt by a subject (at any vertical point along the caudocephalic axis of the body at a distance *r* from the centre of roll) are a better predictor of motion sickness than the forces at the centre of roll.

For the combined lateral and roll oscillations studied in this thesis, the model predicts

$$|e| = \left[\left(k_{y,oto} \cdot f'_y - k_{y,scc} \cdot g \cdot \varphi\right)^2 + \left(k_{z,oto} \cdot f'_z - k_{scc} \cdot g\right)^2\right]^{1/2}$$
$$|e| = \left[\left(k_{y,oto} \cdot \left\{f_y \cdot (1-p) + r \cdot \ddot{\varphi}\right\} + k_{y,scc} \cdot f_y \cdot p\right)^2 + \left(k_{z,oto} \cdot \left\{g + r \cdot \dot{\varphi}^2\right\} - k_{scc} \cdot g\right)^2\right]^{1/2}$$

If assuming fully roll-compensated (p = 1) harmonic lateral oscillation, with an angular frequency ω, then the roll velocity and roll acceleration terms are given by

$$\varphi(t) = -\frac{f_{y0}}{g} \cdot \sin \omega t$$

$$\dot{\varphi}(t) = \frac{d\varphi(t)}{dt} = -\omega \cdot \frac{f_{y0}}{g} \cdot \cos \omega t$$

$$\ddot{\varphi}(t) = \frac{d\dot{\varphi}(t)}{dt} = \omega^2 \cdot \frac{f_{y0}}{g} \cdot \sin \omega t$$

Thus, when using small angle approximations the model assumes that motion sickness can be predicted from the sensation at a point located at a distance r from the centre of roll:

$$|e| = \left[f_y^2 \cdot \left(k_{y,oto} \cdot r \cdot \frac{\omega^2}{g} + k_{y,scc} \right)^2 + g^2 \cdot \left(k_{z,oto} - k_{scc} \right)^2 \right]^{1/2}$$

It is hypothesised that if i) the model parameters $k_{y,oto}$, $k_{z,oto}$, $k_{y,scc}$ and $k_{z,scc}$ are held constant; ii) the oscillation conditions are fixed such that the variables f_y and ω are also constant; and iii) the centre of roll from an arbitrary reference point, r, is varied in successive conditions, then a new parameter, R, may be introduced into the model:

$$|e| = \left[f_y^2 \cdot \left(k_{y,oto} \cdot (r - R) \cdot \frac{\omega^2}{g} + k_{y,scc} \right)^2 + g^2 \cdot \left(k_{z,oto} - k_{scc} \right)^2 \right]^{1/2}$$

It is hypothesised that if the model is optimised to fit the data then the parameter R will be related to the location at which motion sensation is referenced, such that motion sickness can be minimised by minimising the force at location R.

CHAPTER 11 CONCLUSIONS

The magnitude and frequency ranges of the Earth-lateral, coach-lateral and coach-vertical accelerations, and the roll displacements experienced in a tilting-TGV train were calculated. The extent to which a tilting-train compensated for Earth-lateral accelerations was found to be approximately constant with oscillation frequencies up to 0.125 Hz and the range of compensations varied between about 40 and 90%.

There was no significant difference in the amount of sickness produced by sinusoidal and random lateral motion waveforms. It was tentatively concluded that for a given centre frequency and root-mean-square acceleration magnitude, the amount of sickness produced by lateral oscillation was independent of the motion waveform.

For 0.0315 to 0.2 Hz lateral oscillations having the same peak velocity, motion sickness increased with increasing oscillation frequency. It was suggested that the susceptibility to motion sickness with Earth-lateral acceleration may be predicted by an acceleration frequency weighting that is independent of frequency from 0.0315 to 0.25 Hz and reduces at 6 dB/octave (i.e. proportional to velocity) in the range 0.25 to 0.8 Hz. Frequency weightings calculated by normalising motion sickness with the acceleration magnitude measured in the axis of stimulation predicted differing susceptibilities to motion sickness with lateral and vertical oscillations.

Reports of motion sickness with lateral and roll oscillation cannot be predicted from either the roll or lateral motion information alone. In conditions of lateral oscillation where roll is added to remove the lateral forces felt by subjects there will be significantly more motion sickness than if there were no roll motion added. With oscillations in the range from 0.05 to 0.315 Hz, the effect of oscillation frequency on motion sickness with 100% roll-compensation was similar to that found with uncompensated lateral oscillations.

With lateral oscillation at either 0.1 Hz or 0.2 Hz and roll-compensation in the range from 0 to 100%, motion sickness was dependent on the percentage of roll-compensation. The effect of percentage compensation on motion sickness was not predicted simply by models using only lateral motions, only roll motions, or a linear addition of the two.

A motion sickness model based on the concept of sensory conflict and derived from postulates by Stott predicted changes in motion sickness with different combinations of lateral and roll oscillations; however, a model with a unique set of parameters was not found. When motion sickness was normalised by the gravito-inertial force magnitude, similar frequency weightings were found for uncompensated and fully roll-compensated lateral oscillations and for vertical oscillations.

APPENDICES

APPENDIX A – ROTATIONAL COORDINATE SYSTEMS

Rotating coordinate systems are intrinsically non-inertial: rotational motion is accelerating motion. One means of comparing a force vector observed in an inertial system and a rotating system is to find the transformation relating the coordinate systems (e.g. using a rotation matrix) and then to differentiate. Mathematically the description of such a transformation is problematical as angular displacements are not commutative.[16] Instead a transformation rule relating the time derivatives of any vector (e.g. force or acceleration) in inertial and rotating coordinates can be defined (Kleppner & Kolenkow, 1978; Spiegel, 1967):

$$\left.\frac{d\mathbf{f}}{dt}\right|_{Inertial} = \left.\frac{d\mathbf{f}}{dt}\right|_{Rotating} + \boldsymbol{\omega} \wedge \mathbf{f}$$

where $\wedge$ denotes the vector cross product operator and $\boldsymbol{\omega}$ denotes the three dimensional angular velocity of the rotating coordinate system with respect to the inertial system.

It follows that

$$\left.\frac{d\mathbf{g}}{dt}\right|_{Inertial} = \left.\frac{d\mathbf{g}}{dt}\right|_{Rotating} + \boldsymbol{\omega} \wedge \mathbf{g}$$

In an inertial geocentric coordinate system, the force due to gravity can be assumed to be invariant with respect to time, such that the time derivative is zero. The rate of change of gravity in a rotating reference frame is then given by

$$\left.\frac{d\mathbf{g}}{dt}\right|_{Rotating} = -\boldsymbol{\omega} \wedge \mathbf{g}$$

The measurement and resolution of gravito-inertial forces in a translating and rotating environment will depend on knowledge of angular velocity of the rotating system with respect to the inertial geocentric system.

---

[16] The order of rotation matters: a rotation of a rigid body about it's y-axis followed by a rotation about it's z-axis does not produce the same resultant orientation as a rotation of a body about it's z-axis followed by a rotation about it's y-axis.

APPENDIX B – ROLL DISPLACEMENT TO BELT-DISPLACEMENT GEOMETRIC TRANSFORMATION

A geometric transformation relates the belt displacement required to produce a given roll displacement on the motion simulator.

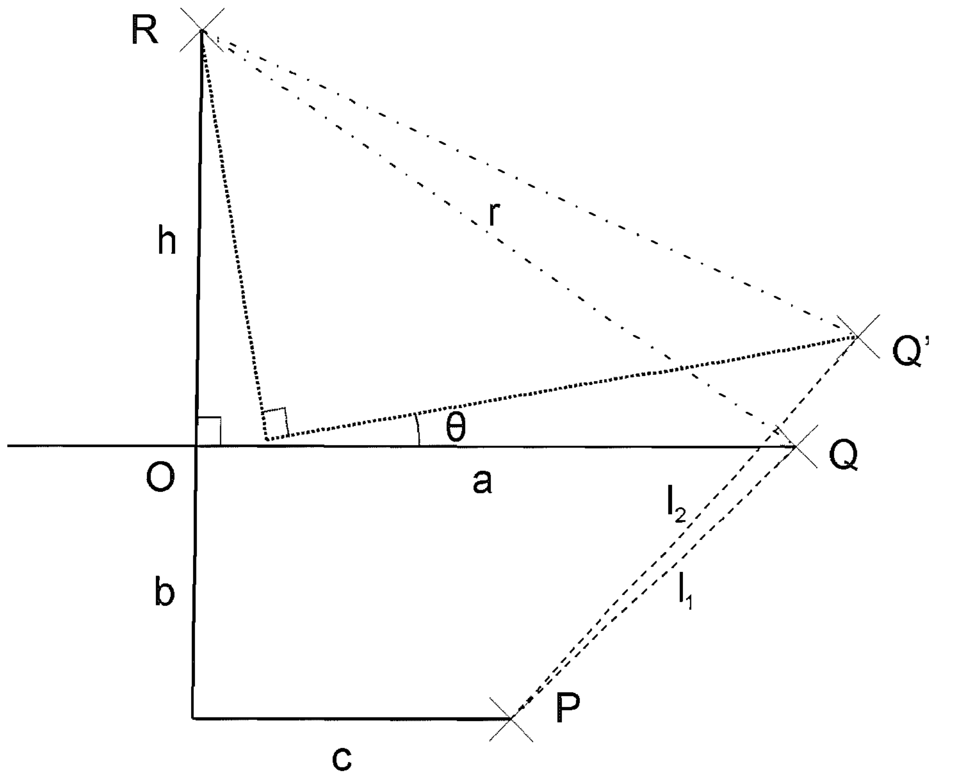

Figure A.1 Co-ordinates and dimensions required to calculate the belt displacement, $l_2 - l_1$, required for a given roll displacement, θ.

With the above dimensions and geometry, the point Q rotates through an arc of radius r, from the centre of roll, R. Using the parameters in Table A.1, with the platform horizontal the angle of RQ from horizontal is $\tan^{-1}(h/a) = 28.85°$. After a roll displacement the angle is: Ø = desired platform angle (θ) minus initial angle of radius of arc from centre of roll (R) horizontal.

Table A.1 Measured and derived dimensions of the roll-rig.

a = 0.962 m b = -0.650 m	$r = \sqrt{a^2 + h^2} = 1.098$ m
c = 0.302 m h = 0.530 m	$Ø = \theta - \tan^{-1}(h/a) = \theta - 28.85$

11.1.1 Definition of co-ordinates

O(0, 0) = origin

$P(x_0, y_0)$ = belt and chassis-pulley contact point: $x_0 = c$, $y_0 = b$

Q(x, y) = initial belt and platform-pulley contact point: x = a, y = 0

Q'(x', y') = displaced belt and platform-pulley contact point: x' = r.cos Ø, y' = r.sin Ø + h

11.1.2 Calculation of the belt displacement required for a given roll

Initial distance between pulleys:

$$l_1 = \sqrt{(x - x_0)^2 + (y - y_0)^2}$$

Distance between pulleys after roll displacement:

$$l_2 = \sqrt{(x' - x_0)^2 + (y' - y_0)^2}$$

Belt displacement required for roll displacement:

$$\Delta l = l_2 - l_1$$

APPENDIX C – MATLAB FUNCTION USED TO CALCULATE MOTION SIGNALS

```
function [t,x,v,a,Rd]=simsig()

% Barnaby Donohew - 30/10/03
% Function: [t,x,v,a,Rd]=simsig()
%
% Creates horizontal and rotational i/p motions for
% 12m horizontal simulator according to user
% specifications.
%

f = input('What is the oscillation frequency ? [Hz] {0.2} ');
if isempty(f), f = 0.2; end

mins = input('What is the signal duration? [mins] {30.5} ');
if isempty(mins), mins = 30.5; end

fs = input('How many samples per second? [samples/sec] {30} ');
if isempty(fs), fs = 30; end

vmax = input('What is the peak velocity ? [m/s] {1.0} ');
if isempty(vmax), vmax = 1.0; end

c = input('What is the proportion of compensation? {1.0} ');
if isempty(c), c = 1.0; end

% phase=input('What phase between rotation and translaton? {2*pi}
');
% if isempty(phase), phase = 2*pi; end

% Ensuring an integer number of wavelengths (W) in the signal
T = 60*mins       % Nominal duration
W = ceil(T.*f);    % Number of whole wavelengths
T = W./f          % Corrected duration
N = T*fs;          % Total number of samples

% Creating velocity signal
t = linspace(0,T-1./fs,N);
v = vmax*cos(2*pi*f*t);

v = intap(v,f,fs);
[t,v] = padends(t,v);
[a,v,x] = intzero(v,t,f,fs);

% Horizontal motion signal
voltH = v.*0.5;

% Creating rotational signal
alpha = atan(a/9.81);
A = sqrt(a'.*a' + 9.81^2);
Rd = asin((1-c)*a./A') - alpha;

% Rd = asin(-(1-c)*a./9.81);

dl = fnlcalc(0.5296,Rd);
beltv = gradient(dl,1./fs);
voltR = beltv/0.0245/4;
```

```
% write data to HVLAB format with appropriate
% filenames
linfilenum = input('What is the linear file name? ');
hvwrite(linfilenum,length(voltH),fs,0.0,voltH);
fprintf(['H data written as ',num2str(linfilenum),'.dat\n']);

rotfilenum = input('What is the rotation file name? ');
if isempty(rotfilenum), rotfilenum = linfilenum + 1000; end
hvwrite(rotfilenum,length(voltR),fs,0.0,voltR);
fprintf(['R data written as ',num2str(rotfilenum),'.dat\n']);

subplot(3,2,1)
plot(t,x), title('Displacement (m)')%, axis([0 120 -2 2])
subplot(3,2,2)
plot(t,v), axis([0 120 -2 2]), title('Velocity (m/s)')
subplot(3,2,3)
plot(t,a), axis([0 120 -2 2]), title('Acceleration (m/s^2)')
subplot(3,2,4)
plot(t,Rd*360/2/pi),   axis([0   120   -10   10]),   title('Angle
(degrees)')
subplot(3,2,5)
plot(t,a  +  9.81*sin(Rd)),  axis([0  120  -2  2]),  title('Subject
lateral acceleration (m/s^2)')
subplot(3,2,6)
plot(t,voltR), axis([0 120 -5 5]), title('Roll Volts')
return

function v = intap(v,f,fs);
% Cosinusoidal taper for periodic oscillation at frequency f:
% taper length is a half-integer number of wavelengths such that
% the displacement, velocity and acceleration integrate to zero.

N = length(v);
TDuration = 5./(2*f);
TSamples = floor(fs*5./(2*f));
TimeVector = linspace(0,TDuration,TSamples);
Taper = sin(pi/(2*TDuration)*TimeVector);

v(1:TSamples) = v(1:TSamples).*Taper;
v((N-TSamples+1):N) = v((N-TSamples+1):N).*fliplr(Taper);
return

function [a,v,x] = intzero(v,t,f,fs);
% Checks that the velocity, displacement and acceleration
% integrate to zero.

a = gradient(v,1./fs);
a = detrend(a);
x = cumtrapz(t,v);
x = detrend(x);
return

function [t,x] = padends(t,x)
% Pads the ends of the signal X with 10s
% of zeros. The corresponding time vector
% T is also extended by 20s.
```

```
dt = t(2) - t(1);
fs = 1./dt;
T = max(t);
Tp = 10;
Np = Tp*fs;
t = [t linspace(T+dt,T+dt+(2*Tp),2*Np)];
x = [zeros(1,Np) x zeros(1,Np)];
return

function dl=fnlcalc(h,ang);
% Calculates change in belt length, dl, required
% for a given rotational displacement, ang.

a = 0.962;
b = -0.6503;
c = 0.3022;

r = sqrt(a^2+h^2);
theta = ang + atan(a/h);

x0 = c;
x1 = a;
x2 = r*sin(theta);
y0 = b;
y1 = 0;
y2 = -r*cos(theta) + h;

deltaX1 = x1 - x0;
deltaX2 = x2 - x0;
deltaY1 = y1 - y0;
deltaY2 = y2 - y0;

l1 = sqrt(deltaX1^2 + deltaY1^2);
l2 = sqrt(deltaX2.^2 + deltaY2.^2);

dl = l2 - l1;
return


function []=hvwrite(filenum,nsamps,srate,origin,data)
% function to write MATLAB data for CHL ship motions into
% HVLab format.
% written 22 September 1998 TPG
% function []=hvwrite(filenum,nsamps,srate,origin,data)

% calculate increment
increment=1./srate;

% convert filenumber to string and add .dat extension
filenumstr=[num2str(filenum),'.dat'];

% create file with write permission
fid=fopen(filenumstr,'w');

%write header values
%first block
fwrite(fid,[nsamps,srate,origin,increment],'float');
padding=[1:28].*0;
```

```
fwrite(fid,padding,'float');

%second block. set mode to 1 and all other values to 0.
block2=[1:384].*0;
block2(1)=1;
fwrite(fid,block2,'int8');

% write data
fwrite(fid,data,'float');
%close file
fclose(fid);
return
```

APPENDIX D – HEALTH SCREENING QUESTIONNAIRE AND CONSENT FORM

Consent form to be completed by adult subjects who are being paid for their participation in an experiment
(Adults are 18 years of age or older).

Human Experimentation Safety & Ethics Approval Number: ....

Exposure Number: ....

Vibration Experiment Exposure and Consent Form

Before completing this form, please read the 'Information for Subjects' on the reverse side of this sheet.

(i) Name .... (Mr/Mrs/Miss/)

(ii) Do you have any of the conditions listed on the reverse side of this form?................................

(iii) Have you ever suffered any serious illness or injury? ....

(iv) Are you under medical treatment or suffering disability affecting your daily life? ....

....

If your answer is 'YES' to questions (ii), (iii) or (iv), please give details to Experimenter.

I understand that for my participation in this experiment I am to be paid the sum of £.................

for my attendance on .... occasion(s).

DECLARATION

I volunteer to be a subject in a vibration experiment. My replies to the above questions are correct to the best of my belief, and I understand that they will be treated by the experimenter as confidential. I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I undertake to obey the regulations of the laboratory and instructions of the Experimenter regarding safety, subject only to my right to withdraw declared above. The purpose and methods of the research have been explained to me and I have had the opportunity to ask questions.

Signature of Subject .... Date ....

I confirm that I have explained to the subject the purpose and nature of the investigation which has been approved by the Human Experimentation Safety and Ethics Committee.

Signature of Experimenter .... Date ....

Medical assistance is available if required.

Cont/...

This form must be submitted to the Secretary of the Human Experimentation Safety and Ethics Committee on completion of the experiment.

Information for Subjects

Persons with any of the following conditions are usually considered unfit for vibration experiments

Active disease of respiratory system: including recent history of coughing-up blood or chest pain.

Active disease of the gastro-intestinal tract: including internal or external hernia, peptic ulcer, recent gall-bladder disease, rectal prolapse, anal fissure, haemorrhoids or pilonidal sinus.

Active disease of the genito-urinary system: including kidney stones, urinary incontinence or retention or difficulty in micturition.

Active disease of the cardiovascular system: including hypertension requiring treatment, angina of effort, valvular disease of the heart, or haemophilia.

Active disease of the musculo-skeletal system: including degenerative or inflammatory disease of the spine, long bones, or major joints or a history of repeated injury with minor trauma.

Active or chronic disease or disorders of the nervous system: including eye and ear disorders and any disorder involving motor control, wasting of muscles, epilepsy or retinal detachment.

Pregnancy: any woman known to be pregnant should not participate as a subject in a vibration experiment.

Mental Health: subjects must be of sound mind and understanding and not suffering from any mental disorder that would raise doubt as to whether their consent to participate in the experiment was true and informed.

Recent trauma and surgical procedures: persons under medical supervision following surgery or traumatic lesions (e.g. fractures) should not participate in vibration experiments.

Prosthesis: persons with internal or external prosthetic devices normally should not participate in vibration experiments (although dentures need not exclude participation in experiments with low magnitudes of vibration).

Other:

....

(For completion by experimenter)

To be completed by the Experimenter:

<u>VIBRATOR</u>:

<u>DESCRIPTION OF VIBRATION</u>: State <u>levels, frequencies, axes, durations</u> etc. (If subject is in direct or indirect control of the vibration level, also state maximum vibration level for each condition.) Indicate subject posture, seat type, etc. and any other factors affecting subject exposure. Description must be sufficient to enable reader to reproduce a similar exposure pattern.

<u>COMMENTS</u>: (If more space is required, please attach a continuation sheet.)

APPENDIX E – MOTION SICKNESS SUSCEPTIBILITY QUESTIONNAIRE

Reference No.: A/ ....

MOTION SICKNESS SUSCEPTIBILITY QUESTIONNAIRE

INSTRUCTIONS

This questionnaire is primarily concerned with: (i) your susceptibility to motion sickness and, (ii) what types of motion are most effective in causing this sickness.

Please read the questions carefully and answer them **ALL** by either TICKING or FILLING IN the boxes which most closely correspond to you as an individual.

All the information you give is CONFIDENTIAL and will be used for research purposes only.

Thank you very much for your co-operation.

NAME ______________________ AGE ________ SUBJECT NUMBER ______

BODY WEIGHT ________________ HEIGHT ______

1. In the past **YEAR**, how many times have you travelled **AS A PASSENGER** in the following types of transport?

	NEVER	1	2-3	4-15	16-63	64-255	256+
CARS	☐	☐	☐	☐	☐	☐	☐
BUSES	☐	☐	☐	☐	☐	☐	☐
COACHES	☐	☐	☐	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐	☐	☐	☐

2. In the past **YEAR**, how many times have you felt ill, whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	1	2	3	4-7	8-15	16+
CARS	☐	☐	☐	☐	☐	☐	☐
BUSES	☐	☐	☐	☐	☐	☐	☐
COACHES	☐	☐	☐	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐	☐	☐	☐

3. In the past **YEAR**, how many times have you VOMITED whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	1	2	3	4-7	8-15	16+
CARS	☐	☐	☐	☐	☐	☐	☐
BUSES	☐	☐	☐	☐	☐	☐	☐
COACHES	☐	☐	☐	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐	☐	☐	☐

4. Do you **EVER** feel HOT or SWEAT whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	OCCASIONALLY	OFTEN	ALWAYS
CARS	☐	☐	☐	☐
BUSES	☐	☐	☐	☐
COACHES	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐

5. Do you **EVER** suffer from HEADACHES whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	OCCASIONALLY	OFTEN	ALWAYS
CARS	☐	☐	☐	☐
BUSES	☐	☐	☐	☐
COACHES	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐

6. Do you **EVER** suffer from LOSS/CHANGE OF SKIN COLOUR (go pale) whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	OCCASIONALLY	OFTEN	ALWAYS
CARS	☐	☐	☐	☐
BUSES	☐	☐	☐	☐
COACHES	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐

7. Do you **EVER** suffer from MOUTH WATERING whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	OCCASIONALLY	OFTEN	ALWAYS
CARS	☐	☐	☐	☐
BUSES	☐	☐	☐	☐
COACHES	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐

8. Do you **EVER** feel DROWSY whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	OCCASIONALLY	OFTEN	ALWAYS
CARS	☐	☐	☐	☐
BUSES	☐	☐	☐	☐
COACHES	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐

9. Do you **EVER** feel DIZZY whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	OCCASIONALLY	OFTEN	ALWAYS
CARS	☐	☐	☐	☐
BUSES	☐	☐	☐	☐
COACHES	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐

10. Do you **EVER** suffer from NAUSEA (stomach discomfort, feeling sick) whilst travelling **AS A PASSENGER** in the following types of transport?

	NEVER	OCCASIONALLY	OFTEN	ALWAYS
CARS	☐	☐	☐	☐
BUSES	☐	☐	☐	☐
COACHES	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐

11. Have you **EVER** VOMITED whilst travelling **AS A PASSENGER** in the following types of transport?

	NO	YES	DON'T KNOW
CARS	☐	☐	☐
BUSES	☐	☐	☐
COACHES	☐	☐	☐
SMALL BOATS	☐	☐	☐
SHIPS	☐	☐	☐
AEROPLANES	☐	☐	☐
TRAINS	☐	☐	☐

12. Would you avoid any of the following types of transport because of motion sickness?

	NEVER	OCCASIONALLY	OFTEN	ALWAYS
CARS	☐	☐	☐	☐
BUSES	☐	☐	☐	☐
COACHES	☐	☐	☐	☐
SMALL BOATS	☐	☐	☐	☐
SHIPS	☐	☐	☐	☐
AEROPLANES	☐	☐	☐	☐
TRAINS	☐	☐	☐	☐

13. Which of the following best describes your SUSCEPTIBILITY to motion sickness?

MUCH LESS THAN AVERAGE	☐
LESS THAN AVERAGE	☐
AVERAGE	☐
MORE THAN AVERAGE	☐
MUCH MORE THAN AVERAGE	☐

14. Have you ever suffered from any serious illness or injury?

YES ☐ NO ☐

15. Are you under medical treatment or suffering a disability affecting daily life?

YES ☐ NO ☐

APPENDIX F – INSTRUCTION SHEET

INSTRUCTION FORM

You will be taking part in an experiment with the aim of investigating the motion sickness response caused by motions typical of tilting trains.

- A motion sickness susceptibility questionnaire and vibration exposure consent and screening form should be completed.
- When on the seat in the simulator cabin, you will be strapped in using a lap belt.
- Please assume a relaxed but upright posture when seated, keeping your hands in your lap and your feet square on the floor.
- Keep your eyes open and look straight ahead at the fractal pattern in front of you.
- Put on the headphones supplied.
- When ready, the motion will start and the experiment will commence.
- The experimenter will ask you how you feel **every minute** during the experiment. You should answer with a number from the table below corresponding to your feelings:

Rating Number	Corresponding Feelings
0	No symptoms
1	Any symptoms, however slight
2	Mild symptoms, e.g. stomach awareness, but no nausea
3	Mild nausea
4	Mild to moderate nausea
5	Moderate nausea but can continue
6	Moderate nausea and want to stop

- The experiment will end either after 30 minutes, or when you have reached a rating of 6.

YOU ARE ABLE TO TERMINATE THE EXPERIMENT AT ANY TIME WITHOUT GIVING A REASON: The experiment can be stopped using the emergency stop button or by signalling verbally.

- At the end of the experiment the simulator will stop. You should remain still with your eyes kept open.
- A post-experiment symptom checklist should be completed.

IF YOU FEEL NAUSEOUS OR UNSTEADY AFTER THE EXPERIMENT, YOU SHOULD NOT DRIVE OR OPERATE MACHINERY UNTIL YOU FEEL ABLE TO DO SO SAFELY.

Thank you for taking part in this experiment.

APPENDIX G – SYMPTOM CHECKLIST

SYMPTOM CHECKLIST

SUBJECT NUMBER _____ CONDITION _______

If you experienced any of the symptoms below whilst you were in the car, please place a tick in the relevant box. (You may tick more than one box).

	YES	NO
YAWNING	☐	☐
COLD SWEATING	☐	☐
NAUSEA	☐	☐
STOMACH AWARENESS	☐	☐
DRY MOUTH	☐	☐
INCREASED SALIVATION	☐	☐
HEADACHE	☐	☐
BODILY WARMTH	☐	☐
DIZZY	☐	☐
DROWSY	☐	☐

APPENDIX H – STATISTICAL POWER PARAMETER CALCULATION

The statistical power has been calculated for a comparison of the relative effects on motion sickness of sinusoidal and octave-band random motion. The method is detailed below.

The power calculation assumes a comparison of means using a Student's *t*-test. For the *t*-test, the power calculation requires the following parameters: the numbers of subjects, the mean, the standard deviation and the desired significance level (α). Table A.2 tabulates the number of subjects and the means and the standard deviations of the average illness ratings reported in the octave-band random and sinusoidal motion conditions.

Calculation of the power occurs in two steps: the first step involves calculating the test statistic required for significance, in this case given by a central *t*-distribution for the desired significance level (α = 0.05 for this study), the type of test, and the degrees of freedom, *df*. The average illness ratings were compared using a two-tailed test with 27 degrees of freedom such that the *t*-test statistic (typically found in statistical tables) required for the desired significance level ($\alpha/2 = 0.05/2 = 0.025$) was 2.052. The second step involves calculation of the power from the non-central *t* distribution, given a non-centrality parameter, δ, the *t*-statistic required for significance and the degrees of freedom, *df*.

The non-centrality parameter is dependent on the effect size of interest, *d*, and the harmonic mean number of subjects, n_h. The effect size is defined as the ratio of the mean difference to the pooled standard deviation.

The effect size can be calculated for the data in Table A.2: The mean difference is given by

$$m_d = |m_1 - m_2| = |1.50 - 1.08| = 0.420$$

and the pooled standard deviation is given by

$$s = \sqrt{\frac{(n_1 - 1) \cdot s_1^2 + (n_2 - 1) \cdot s_2^2}{df}} = \sqrt{\frac{16 \times 1.60^2 + 11 \times 1.12^2}{27}} = 1.424$$

The effect size is then

$$d = \frac{m_d}{s} = \frac{0.420}{1.424} = 0.295$$

The harmonic mean number of subjects also follows:

$$s = \frac{2 \cdot n_1 \cdot n_2}{n_1 + n_2} = \frac{2 \times 17 \times 12}{17 + 12} = 14.069$$

The non-centrality parameter for the test of interest is then given by

$$\delta = \left| d \cdot \sqrt{\frac{n_h}{2}} \right| = \left| 0.295 \cdot \sqrt{\frac{14.069}{2}} \right| = 0.7824$$

Calculations using the SamplePower program (version 1.20, 1997; SPSS Inc.) estimated the power as 11.7%.

Table A.2 Numbers of subjects and the mean and standard deviation average illness rating reported in the octave-band random and sinusoidal motion waveform conditions.

Motion Condition	N	Mean illness rating	Standard deviation
Octave-band random	17	1.50	1.60
Sinusoidal	12	1.08	1.12

APPENDIX I – CALCULATION OF THE ROLL ANGLE REQUIRED FOR A DESIRED COMPENSATION RATIO

With roll compensated lateral oscillation, the desired roll angle of a subject about the Earth's *x*-axis, φ, is given by the angular difference between the desired orientation of the gravito-inertial force relative to the subject-referenced coordinate system, α, and the orientation of the gravito-inertial force relative to the Earth-referenced coordinate system, θ:

$$\varphi = \alpha - \theta$$

$$\alpha = \arctan\left(\frac{f'_y}{f'_z}\right)$$

$$\theta = \arctan\left(\frac{f_y}{f_z}\right)$$

$$\varphi = \arctan\left(\frac{f'_y}{f'_z}\right) - \arctan\left(\frac{f_y}{f_z}\right)$$

Using the trigonometric identity

$$\tan(\varphi) = \tan(\alpha - \theta)$$

$$\tan(\varphi) = \frac{\tan\alpha - \tan\theta}{1 - \tan\alpha \cdot \tan\theta}$$

If follows that

$$\tan\alpha = \frac{f'_y}{f'_z}$$

$$\tan\theta = \frac{f_y}{f_z}$$

From substitution

$$\tan(\varphi) = \frac{\frac{f'_y}{f'_z} - \frac{f_y}{f_z}}{1 - \frac{f'_y}{f'_z} \cdot \frac{f_y}{f_z}}$$

$$\tan(\varphi) = \frac{f'_y \cdot f'_z - f_y \cdot f_z}{f_z \cdot f'_z - \cdot f_y \cdot f'_y}$$

Substituting the Earth and subject referenced forces gives the roll displacement of the subject as a function of the Earth-referenced forces and the compensation ratio:

$$\varphi = -\arctan\left(\frac{g \cdot f_y \cdot (1-p) + f_y \cdot \sqrt{g^2 + f_y^2 \cdot (2 \cdot p - p^2)}}{g \cdot \sqrt{g^2 + f_y^2 \cdot (2 \cdot p - p^2)} + f_y^2 \cdot (1-p)}\right)$$

The equation simplifies if it is assumed that $|f_y| << |g|$

$$\varphi = -\arctan\left(\frac{f_y \cdot p}{g}\right)$$

The cosines of this angle are given by:

$$\sin\varphi = -\frac{f_y \cdot p}{g \cdot \sqrt{1 + \frac{f_y^2 \cdot p^2}{g^2}}}$$

$$\cos\varphi = \frac{1}{\sqrt{1 + \frac{f_y^2 \cdot p^2}{g^2}}}$$

The cosines simplify by repeating the assumption ($|f_y| << |g|$)

$$\sin\varphi = -\frac{f_y \cdot p}{g}$$

$$\cos\varphi = 1$$

APPENDIX J – EXPERIMENTAL DATA

Test identification			Test motion			Illness rating measures				Reach illness rating						Time to reach illness rating						Motion sickness susceptibility measures							Symptoms										
Experiment	Condition	Subject number	Frequency (Hz)	Acceleration (m/s^2 r.m.s)	Compensation (%)	30th minute	Mean	Median	Maximum	1	2	3	4	5	6	1	2	3	4	5	6	Age (Years)	Mtotal	Isusc.(yr.)	Vsusc.(yr.)	Vtotal	Mland	Mnon-land	Yawning	Cold sweating	Nausea	Stomach awareness	Dry mouth	Increased salivation	Headache	Bodily warmth	Dizzy	Drowsy	Total symptom score
1	1	1	0.2	0.44	0	3	1.8	2	4	1	1	1	1	0	0	2	13	20	28	30	30	24	7	0.00	0.00	0	4	3	0	1	1	1	0	0	1	1	0	0	5
1	1	2	0.2	0.44	0	6	4.0	6	6	1	1	1	1	1	1	2	6	13	15	15	15	18	20	0.00	0.00	0	14	7	0	0	1	1	1	0	0	0	1	1	5
1	1	3	0.2	0.44	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	23	-2	0.00	0.00	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0
1	1	4	0.2	0.44	0	1	0.8	1	1	1	0	0	0	0	0	6	30	30	30	30	30	24	13	0.33	0.00	4	7	6	1	0	0	0	0	0	0	0	0	1	2
1	1	5	0.2	0.44	0	1	1.1	1	2	1	1	0	0	0	0	6	21	30	30	30	30	22	6	0.16	0.00	2	5	0	1	0	0	1	0	0	0	1	1	1	5
1	1	6	0.2	0.44	0	2	1.0	1	2	1	1	0	0	0	0	9	17	30	30	30	30	22	3	0.10	0.00	0	1	1	1	0	0	0	0	0	0	0	1	1	3
1	1	7	0.2	0.44	0	0	0.4	0	1	1	0	0	0	0	0	8	30	30	30	30	30	22	29	0.67	0.00	0	22	5	1	0	0	0	0	0	0	0	0	1	2
1	1	8	0.2	0.44	0	3	0.9	1	3	1	1	1	0	0	0	9	22	30	30	30	30	24	10	0.03	0.00	2	6	4	0	0	1	1	0	1	0	0	0	0	3
1	1	9	0.2	0.44	0	0	0.2	0	1	1	0	0	0	0	0	12	30	30	30	30	30	25	13	0.03	0.00	6	8	4	1	0	0	0	0	0	0	1	0	1	3
1	1	10	0.2	0.44	0	6	4.2	5.5	6	1	1	1	1	1	1	4	6	8	12	14	16	22	42	0.23	0.00	4	22	21	1	1	1	1	1	1	0	1	1	1	9
1	1	11	0.2	0.44	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	24	-2	0.00	0.00	0	-2	-2	1	0	0	0	0	0	0	0	0	0	1
1	1	12	0.2	0.44	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	23	-1	0.00	0.00	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
1	1	13	0.2	0.44	0	2	1.0	1	2	1	1	0	0	0	0	1	29	30	30	30	30	24	-1	0.00	0.00	1	-1	-2	0	0	0	1	1	0	0	1	1	1	5
1	1	14	0.2	0.44	0	5	2.9	3	5	1	1	1	1	1	0	3	7	12	18	27	30	19	4	0.00	0.00	0	3	0	0	0	1	1	1	1	0	0	1	1	6
1	1	15	0.2	0.44	0	3	2.1	2	3	1	1	1	0	0	0	3	4	21	30	30	30	20	25	0.27	0.00	3	20	5	1	0	1	1	0	0	0	0	1	1	5
1	1	16	0.2	0.44	0	6	4.9	6	6	1	1	1	1	1	1	2	3	6	7	9	11	24	8	0.36	0.00	2	5	1	0	1	1	1	0	1	0	1	0	0	5
1	1	17	0.2	0.44	0	0	0.1	0	2	1	1	0	0	0	0	22	22	30	30	30	30	21	37	0.00	0.00	3	20	17	0	0	0	1	0	0	0	0	0	0	1
2	1	101	0.0315	0.14	0	0	0.0	0	1	1	0	0	0	0	0	17	30	30	30	30	30	20	8	0.00	0.00	0	6	1	1	0	0	0	0	0	0	0	0	0	1
2	1	102	0.0315	0.14	0	0	0.0	0	1	1	0	0	0	0	0	3	30	30	30	30	30	20	2	0.04	0.00	0	-1	2	1	0	0	1	0	0	0	0	0	0	2

2	1	103	0.0315	0.14	0	1	0.3	0	1	1	0	0	0	0	0	21	30	30	30	30	30	19	1	0.00	0.00	0	-1	1	0	0	0	1	0	0	0	0	0	0	1
2	1	104	0.0315	0.14	0	2	1.1	1	2	1	1	0	0	0	0	7	19	30	30	30	30	19	6	0.04	0.00	2	1	3	1	0	0	0	0	0	1	0	0	1	3
2	1	105	0.0315	0.14	0	1	0.8	1	1	1	0	0	0	0	0	4	30	30	30	30	30	20	8	0.00	0.00	0	4	3	0	0	0	0	0	0	0	0	0	1	1
2	1	106	0.0315	0.14	0	1	0.6	1	1	1	0	0	0	0	0	12	30	30	30	30	30	22	29	0.20	0.00	4	13	15	1	1	0	0	1	1	0	1	0	0	5
2	1	107	0.0315	0.14	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	21	4	0.00	0.00	0	3	0	1	0	0	0	0	1	0	0	0	0	2
2	1	108	0.0315	0.14	0	1	0.8	1	2	1	1	0	0	0	0	10	27	30	30	30	30	22	7	0.19	0.00	0	7	-1	1	0	0	0	0	1	1	0	1	0	4
2	1	109	0.0315	0.14	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	5	0.07	0.00	0	2	2	1	0	0	0	0	0	0	0	0	0	1
2	1	110	0.0315	0.14	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	2	0.00	0.00	0	2	-2	0	0	0	0	0	0	0	0	0	0	0
2	1	111	0.0315	0.14	0	4	2.5	3	4	1	1	1	1	0	0	5	8	15	21	30	30	21	35	0.38	0.00	1	26	10	1	0	1	1	1	0	0	0	1	0	5
2	1	112	0.0315	0.14	0	0	0.2	0	1	1	0	0	0	0	0	17	30	30	30	30	30	25	3	0.00	0.00	3	3	0	1	0	0	0	0	1	1	0	0	1	4
2	1	113	0.0315	0.14	0	2	0.9	1	2	1	1	0	0	0	0	1	20	30	30	30	30	21	20	0.00	0.00	0	11	7	1	0	0	0	0	0	0	0	0	1	2
2	1	114	0.0315	0.14	0	1	0.9	1	1	1	0	0	0	0	0	5	30	30	30	30	30	18	11	0.03	0.00	2	4	5	0	0	0	1	0	0	0	0	0	0	1
2	1	115	0.0315	0.14	0	1	1.4	1	2	1	1	0	0	0	0	4	12	30	30	30	30	21	14	0.07	0.00	3	12	1	0	1	1	1	0	1	0	1	0	1	6
2	1	116	0.0315	0.14	0	0	0.4	0	1	1	0	0	0	0	0	4	30	30	30	30	30	21	12	0.10	0.00	1	-1	12	1	0	0	1	0	1	0	0	0	0	3
2	1	117	0.0315	0.14	0	0	0.0	0	1	1	0	0	0	0	0	22	30	30	30	30	30	20	7	0.00	0.00	0	4	2	1	0	0	0	0	0	0	0	0	0	1
2	1	118	0.0315	0.14	0	1	0.3	0	1	1	0	0	0	0	0	16	30	30	30	30	30	22	30	0.00	0.00	1	22	7	1	0	0	0	1	0	0	0	0	1	3
2	1	119	0.0315	0.14	0	1	0.6	1	1	1	0	0	0	0	0	12	30	30	30	30	30	21	12	0.00	0.00	0	9	1	0	0	0	0	0	0	0	0	0	1	1
2	1	120	0.0315	0.14	0	1	1.0	1	2	1	1	0	0	0	0	3	16	30	30	30	30	20	15	0.09	0.00	0	12	2	0	0	0	1	0	0	0	1	0	0	2
2	2	39	0.05	0.22	0	1	0.7	1	1	1	0	0	0	0	0	4	30	30	30	30	30	20	6	0.00	0.00	0	5	-1	0	0	0	1	0	0	0	1	0	1	3
2	2	40	0.05	0.22	0	2	2.2	2	3	1	1	1	0	0	0	2	8	14	30	30	30	23	7	0.00	0.00	2	0	7	0	0	1	0	0	1	0	1	0	1	4
2	2	41	0.05	0.22	0	1	0.9	1	1	1	0	0	0	0	0	3	30	30	30	30	30	20	2	0.00	0.00	0	0	0	1	0	0	0	1	1	0	0	0	1	4
2	2	42	0.05	0.22	0	0	0.1	0	1	1	0	0	0	0	0	1	30	30	30	30	30	21	1	0.00	0.00	0	0	0	0	0	0	1	0	0	0	1	0	0	2
2	2	43	0.05	0.22	0	1	1.0	1	2	1	1	0	0	0	0	4	16	30	30	30	30	19	2	0.00	0.00	0	2	-2	1	0	0	1	0	0	0	0	0	1	3
2	2	44	0.05	0.22	0	0	0.1	0	1	1	0	0	0	0	0	1	30	30	30	30	30	22	10	0.00	0.00	0	8	2	0	0	0	0	0	0	0	0	0	0	0
2	2	45	0.05	0.22	0	2	1.7	2	2	1	1	0	0	0	0	2	8	30	30	30	30	21	19	0.20	0.00	2	6	14	1	0	0	0	0	0	1	1	1	1	5
2	2	46	0.05	0.22	0	0	0.1	0	1	1	0	0	0	0	0	11	30	30	30	30	30	24	1	0.00	0.00	1	0	-1	0	0	0	0	0	0	0	0	1	0	1
2	2	49	0.05	0.22	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	29	0.00	0.00	2	14	13	0	0	0	0	0	0	0	0	0	0	0
2	2	50	0.05	0.22	0	2	1.3	2	2	1	1	0	0	0	0	8	15	30	30	30	30	18	6	0.00	0.00	0	3	1	0	0	0	0	0	1	0	0	0	1	2
2	2	51	0.05	0.22	0	1	0.7	1	1	1	0	0	0	0	0	9	30	30	30	30	30	18	-1	0.08	0.00	0	-1	-1	1	0	0	0	1	0	0	1	0	0	3
2	2	52	0.05	0.22	0	2	1.3	1	2	1	1	0	0	0	0	6	18	30	30	30	30	19	17	0.30	0.00	0	14	2	1	0	1	1	1	0	1	0	0	1	6
2	2	53	0.05	0.22	0	2	0.8	1	2	1	1	0	0	0	0	10	25	30	30	30	30	19	3	0.04	0.00	0	2	-1	1	0	0	0	0	0	0	0	0	1	2
2	2	54	0.05	0.22	0	2	0.3	0	2	1	1	0	0	0	0	24	28	30	30	30	30	19	1	0.00	0.00	0	1	-2	0	0	0	0	0	0	0	1	0	1	2
2	2	55	0.05	0.22	0	0	0.8	1	2	1	1	0	0	0	0	8	20	30	30	30	30	18	17	0.12	0.00	1	5	12	0	1	0	0	0	1	0	1	0	1	4

2	2	58	0.05	0.22	0	4	1.9	2	4	1	1	1	1	0	0	7	14	18	27	30	30	20	43	0.00	0.00	2	15	28	0	0	1	1	0	1	0	1	0	1	5
2	2	62	0.05	0.22	0	1	0.9	1	2	1	1	0	0	0	0	9	13	30	30	30	30	25	6	0.00	0.00	0	5	1	1	0	0	1	0	0	1	0	1	0	4
2	2	63	0.05	0.22	0	1	1.1	1	2	1	1	0	0	0	0	4	18	30	30	30	30	20	19	0.00	0.00	0	12	6	1	0	0	1	0	1	0	1	0	1	5
2	2	64	0.05	0.22	0	0	0.4	0	1	1	0	0	0	0	0	6	30	30	30	30	30	20	-1	0.00	0.00	0	-1	-1	0	0	0	1	0	0	0	0	1	0	2
2	2	69	0.05	0.22	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	21	11	0.00	0.00	1	8	1	0	0	0	0	0	0	0	0	0	0	0
2	3	56	0.08	0.36	0	2	1.8	2	2	1	1	0	0	0	0	3	4	30	30	30	30	18	17	0.07	0.00	0	9	6	1	1	0	0	0	0	1	0	0	1	4
2	3	57	0.08	0.36	0	2	0.7	0	2	1	1	0	0	0	0	18	22	30	30	30	30	19	3	0.00	0.00	0	3	-1	1	0	0	0	0	1	0	0	0	1	3
2	3	59	0.08	0.36	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	19	3	0.00	0.00	0	3	0	0	0	0	0	0	0	0	0	0	0	0
2	3	60	0.08	0.36	0	1	0.7	1	1	1	0	0	0	0	0	9	30	30	30	30	30	23	4	0.17	0.00	0	4	-2	1	0	0	0	0	0	1	0	0	0	2
2	3	61	0.08	0.36	0	1	0.9	1	1	1	0	0	0	0	0	4	30	30	30	30	30	21	5	0.00	0.00	0	3	1	1	0	0	0	0	1	0	1	0	1	4
2	3	65	0.08	0.36	0	0	0.3	0	1	1	0	0	0	0	0	9	30	30	30	30	30	18	19	0.07	0.00	0	5	14	1	0	0	0	0	0	0	0	0	1	2
2	3	66	0.08	0.36	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	21	12	0.00	0.00	1	7	5	0	0	0	0	0	0	0	0	0	0	0
2	3	67	0.08	0.36	0	2	1.2	1	2	1	1	0	0	0	0	6	20	30	30	30	30	19	4	0.05	0.00	0	0	2	1	0	0	0	0	1	0	0	0	1	3
2	3	68	0.08	0.36	0	1	0.9	1	2	1	1	0	0	0	0	5	9	30	30	30	30	18	6	0.10	0.00	1	5	-1	1	0	0	1	0	1	0	1	0	0	4
2	3	70	0.08	0.36	0	0	0.1	0	1	1	0	0	0	0	0	26	30	30	30	30	30	23	7	0.00	0.00	2	0	7	0	0	0	0	0	1	0	0	0	0	1
2	3	71	0.08	0.36	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	11	0.00	0.00	1	9	1	1	0	0	0	0	0	0	0	0	0	1
2	3	72	0.08	0.36	0	2	2.1	2	3	1	1	1	0	0	0	2	5	10	30	30	30	20	31	0.05	0.00	1	18	11	1	0	1	1	0	1	1	0	0	1	6
2	3	73	0.08	0.36	0	3	2.3	3	3	1	1	1	0	0	0	2	9	14	30	30	30	20	10	0.00	0.00	0	1	8	1	0	1	1	0	1	1	1	1	1	8
2	3	74	0.08	0.36	0	2	1.4	2	2	1	1	0	0	0	0	8	13	30	30	30	30	20	13	0.12	0.00	1	11	1	1	0	0	0	0	0	0	0	0	1	2
2	3	75	0.08	0.36	0	3	1.7	2	3	1	1	1	0	0	0	6	13	22	30	30	30	20	11	0.05	0.00	5	2	8	1	0	1	0	0	0	0	1	1	0	4
2	3	76	0.08	0.36	0	0	0.7	1	1	1	0	0	0	0	0	6	30	30	30	30	30	22	-2	0.00	0.00	0	-2	-2	1	0	0	0	0	0	0	1	0	1	3
2	3	77	0.08	0.36	0	0	0.4	0	2	1	1	0	0	0	0	4	27	30	30	30	30	21	9	0.00	0.00	4	4	3	0	0	0	1	0	0	0	0	0	0	1
2	3	78	0.08	0.36	0	1	0.8	1	2	1	1	0	0	0	0	5	18	30	30	30	30	21	-1	0.00	0.00	0	-1	-2	0	0	0	1	0	0	1	0	0	1	3
2	3	79	0.08	0.36	0	0	0.1	0	1	1	0	0	0	0	0	7	30	30	30	30	30	21	8	0.18	0.00	0	7	0	1	0	0	0	0	0	0	0	0	0	1
2	3	80	0.08	0.36	0	0	0.1	0	1	1	0	0	0	0	0	2	30	30	30	30	30	21	19	0.11	0.00	2	10	8	1	0	0	0	1	0	1	0	1	1	5
2	4	1	0.125	0.56	0	1	0.9	1	1	1	0	0	0	0	0	5	30	30	30	30	30	20	16	0.00	0.00	1	12	3	1	0	0	0	0	0	0	1	0	1	3
2	4	2	0.125	0.56	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	19	-2	0.00	0.00	0	-2	-2	1	0	0	0	1	0	0	0	0	0	2
2	4	3	0.125	0.56	0	1	0.8	1	1	1	0	0	0	0	0	6	30	30	30	30	30	21	3	0.00	0.00	2	2	0	0	0	0	0	0	0	0	0	1	1	2
2	4	4	0.125	0.56	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	23	-1	0.00	0.00	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
2	4	5	0.125	0.56	0	1	0.4	0	1	1	0	0	0	0	0	9	30	30	30	30	30	20	-2	0.00	0.00	0	-2	-2	1	0	0	0	0	0	0	0	1	0	2
2	4	6	0.125	0.56	0	2	1.3	1.5	2	1	1	0	0	0	0	5	16	30	30	30	30	19	6	0.00	0.00	1	2	2	1	0	0	0	1	0	0	0	0	1	3
2	4	7	0.125	0.56	0	1	0.7	1	1	1	0	0	0	0	0	10	30	30	30	30	30	20	12	0.00	0.00	1	6	5	0	0	0	0	0	0	0	1	1	1	3
2	4	8	0.125	0.56	0	2	1.2	1	2	1	1	0	0	0	0	5	19	30	30	30	30	20	13	0.24	0.04	2	4	8	1	1	0	1	0	0	1	0	0	1	5

2	4	9	0.125	0.56	0	4	3.0	4	4	1	1	1	1	0	0	2	6	10	15	30	30	18	13	0.29	0.00	4	7	6	1	0	1	1	1	1	0	0	0	1	6
2	4	10	0.125	0.56	0	1	1.4	1	3	1	1	1	0	0	0	4	10	14	30	30	30	18	8	0.00	0.00	0	4	4	1	1	1	0	1	0	0	1	0	1	6
2	4	11	0.125	0.56	0	0	0.4	0	1	1	0	0	0	0	0	5	30	30	30	30	30	18	15	0.10	0.00	1	11	4	0	0	0	0	0	1	0	0	1	1	3
2	4	12	0.125	0.56	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	18	-2	0.00	0.00	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0
2	4	13	0.125	0.56	0	0	0.1	0	1	1	0	0	0	0	0	6	30	30	30	30	30	24	4	0.00	0.00	2	1	2	1	0	0	1	0	1	0	0	0	1	4
2	4	14	0.125	0.56	0	3	1.4	1	3	1	1	1	0	0	0	6	14	29	30	30	30	18	5	0.04	0.04	3	4	0	1	0	1	1	0	1	1	0	1	1	7
2	4	15	0.125	0.56	0	2	1.9	2	3	1	1	1	0	0	0	3	7	12	30	30	30	23	19	0.17	0.00	1	13	5	0	0	1	1	1	1	0	1	0	1	6
2	4	16	0.125	0.56	0	4	2.8	3	4	1	1	1	1	0	0	1	8	11	19	30	30	19	11	0.08	0.00	1	5	6	0	1	1	1	0	0	0	1	1	0	5
2	4	21	0.125	0.56	0	2	1.8	2	3	1	1	1	0	0	0	3	7	18	30	30	30	22	19	0.03	0.00	2	4	14	1	1	1	1	0	1	0	0	1	1	7
2	4	29	0.125	0.56	0	0	1.6	2	2	1	1	0	0	0	0	2	3	30	30	30	30	20	23	0.24	0.00	1	9	13	1	0	0	1	0	1	0	0	1	1	5
2	4	34	0.125	0.56	0	2	1.1	1	2	1	1	0	0	0	0	6	16	30	30	30	30	19	41	0.48	0.00	3	13	28	1	0	0	0	0	0	1	0	0	0	2
2	4	47	0.125	0.56	0	0	0.4	0	2	1	1	0	0	0	0	2	7	30	30	30	30	23	7	0.00	0.00	0	5	1	0	0	0	1	1	0	0	0	0	1	3
2	5	81	0.16	0.71	0	1	2.0	2	3	1	1	1	0	0	0	2	3	6	30	30	30	20	10	0.17	0.00	2	6	3	1	1	1	1	1	0	1	1	0	1	8
2	5	82	0.16	0.71	0	2	1.6	2	2	1	1	0	0	0	0	5	8	30	30	30	30	21	20	0.32	0.00	1	13	6	1	0	0	0	0	0	1	1	0	1	4
2	5	83	0.16	0.71	0	2	1.2	1	2	1	1	0	0	0	0	1	14	30	30	30	30	20	42	0.11	0.06	1	23	18	0	1	0	1	0	0	0	1	1	0	4
2	5	84	0.16	0.71	0	6	4.0	5	6	1	1	1	1	1	1	3	6	7	14	15	19	24	20	0.28	0.00	1	12	7	0	0	1	1	1	1	0	1	1	0	6
2	5	85	0.16	0.71	0	3	1.3	1	3	1	1	1	0	0	0	6	19	30	30	30	30	19	2	0.00	0.00	1	2	-1	0	0	1	1	0	1	0	0	0	0	3
2	5	86	0.16	0.71	0	5	3.4	3.5	5	1	1	1	1	1	0	1	4	9	16	23	30	20	10	0.15	0.00	0	4	6	0	0	1	1	0	0	1	1	1	1	6
2	5	87	0.16	0.71	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	-1	0.00	0.00	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
2	5	88	0.16	0.71	0	2	1.5	2	2	1	1	0	0	0	0	6	11	30	30	30	30	20	11	0.13	0.00	0	11	0	0	0	0	1	0	1	0	0	0	1	3
2	5	89	0.16	0.71	0	1	1.1	1	2	1	1	0	0	0	0	5	12	30	30	30	30	20	13	0.14	0.00	1	3	8	1	0	0	1	0	0	0	1	0	1	4
2	5	90	0.16	0.71	0	2	1.7	2	3	1	1	1	0	0	0	6	9	13	30	30	30	21	8	0.00	0.00	2	4	2	0	0	1	1	0	0	0	0	0	1	3
2	5	91	0.16	0.71	0	2	1.3	2	2	1	1	0	0	0	0	9	14	30	30	30	30	18	6	0.27	0.00	0	1	4	0	0	0	1	0	0	1	0	0	1	3
2	5	92	0.16	0.71	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	21	6	0.13	0.00	2	2	3	1	0	0	0	0	0	0	1	0	1	3
2	5	93	0.16	0.71	0	2	1.3	2	2	1	1	0	0	0	0	8	12	30	30	30	30	22	6	0.00	0.00	3	1	3	0	0	0	1	0	0	0	0	0	0	1
2	5	94	0.16	0.71	0	1	1.5	1.5	2	1	1	0	0	0	0	2	15	30	30	30	30	22	15	0.00	0.00	2	10	4	0	0	0	0	0	1	1	0	0	1	3
2	5	95	0.16	0.71	0	2	1.4	1	3	1	1	1	0	0	0	1	9	26	30	30	30	22	16	0.00	0.00	0	14	1	1	0	1	0	0	1	1	0	0	1	5
2	5	96	0.16	0.71	0	3	1.7	2	3	1	1	1	0	0	0	7	12	20	30	30	30	19	1	0.07	0.00	0	-1	1	1	1	1	0	0	1	1	0	0	1	6
2	5	97	0.16	0.71	0	3	2.6	3	3	1	1	1	0	0	0	1	5	9	30	30	30	19	20	0.32	0.00	0	12	7	1	0	1	1	0	1	0	0	1	1	6
2	5	98	0.16	0.71	0	1	1.0	1	2	1	1	0	0	0	0	4	14	30	30	30	30	19	15	0.27	0.00	1	8	6	1	0	0	1	0	1	0	0	1	1	5
2	5	99	0.16	0.71	0	1	0.6	1	1	1	0	0	0	0	0	14	30	30	30	30	30	19	5	0.07	0.00	1	4	0	0	0	0	0	1	0	0	0	1	1	3
2	5	100	0.16	0.71	0	3	1.9	2	3	1	1	1	0	0	0	6	12	17	30	30	30	19	7	0.12	0.00	0	3	3	0	0	1	1	1	1	0	0	1	0	5
2	6	17	0.2	0.89	0	3	2.1	2	4	1	1	1	1	0	0	3	11	17	26	30	30	25	7	0.00	0.00	0	6	1	0	1	1	1	0	0	1	1	0	0	5

2	6	18	0.2	0.89	0	3	1.5	1.5	3	1	1	1	0	0	0	8	16	21	30	30	30	22	6	0.05	0.00	0	5	0	1	1	1	1	1	0	0	1	0	1	7
2	6	19	0.2	0.89	0	2	1.2	1	2	1	1	0	0	0	0	8	17	30	30	30	30	21	5	0.00	0.00	0	3	0	1	0	0	0	1	0	0	0	1	1	4
2	6	20	0.2	0.89	0	0	0.1	0	1	1	0	0	0	0	0	11	30	30	30	30	30	21	5	0.00	0.00	0	3	0	0	0	0	0	0	1	0	0	0	1	2
2	6	22	0.2	0.89	0	1	0.8	1	1	1	0	0	0	0	0	7	30	30	30	30	30	21	8	0.00	0.00	1	5	2	0	0	0	0	0	0	1	0	1	0	2
2	6	23	0.2	0.89	0	1	1.4	1	3	1	1	1	0	0	0	4	12	24	30	30	30	19	10	0.06	0.00	1	6	3	1	0	1	1	0	0	1	1	1	0	6
2	6	24	0.2	0.89	0	6	2.9	2	6	1	1	1	1	1	1	4	12	18	21	22	22	22	45	0.43	0.00	7	18	27	1	0	0	1	1	0	1	1	1	0	6
2	6	25	0.2	0.89	0	3	1.1	1	3	1	1	1	0	0	0	5	25	29	30	30	30	22	8	0.00	0.00	1	5	1	1	0	1	1	1	0	0	1	0	1	6
2	6	26	0.2	0.89	0	0	0.6	1	1	1	0	0	0	0	0	7	30	30	30	30	30	20	8	0.10	0.00	0	4	2	1	0	0	0	0	0	0	0	0	1	2
2	6	27	0.2	0.89	0	4	2.1	2	4	1	1	1	1	0	0	4	10	19	27	30	30	19	2	0.00	0.00	2	1	0	0	0	1	1	0	1	0	0	0	0	3
2	6	28	0.2	0.89	0	6	4.5	6	6	1	1	1	1	1	1	1	2	6	12	13	13	20	13	0.31	0.00	0	6	7	0	0	1	1	1	0	0	0	0	0	3
2	6	30	0.2	0.89	0	2	1.7	2	2	1	1	0	0	0	0	1	9	30	30	30	30	19	15	0.00	0.00	1	11	2	1	0	0	1	0	0	0	0	1	1	4
2	6	31	0.2	0.89	0	1	0.7	1	2	1	1	0	0	0	0	13	21	30	30	30	30	22	12	0.00	0.00	1	9	1	1	0	0	0	1	0	0	0	0	1	3
2	6	32	0.2	0.89	0	6	5.5	6	6	1	1	1	1	1	1	1	2	2	4	5	7	24	3	0.17	0.00	1	3	-2	0	0	1	1	0	1	1	1	0	1	6
2	6	33	0.2	0.89	0	3	2.1	2.5	3	1	1	1	0	0	0	2	9	14	30	30	30	23	2	0.00	0.00	1	0	1	0	0	1	1	0	1	0	0	0	1	4
2	6	35	0.2	0.89	0	0	1.6	2	2	1	1	0	0	0	0	4	8	30	30	30	30	23	10	0.00	0.00	0	9	0	0	1	0	1	1	0	1	0	1	1	6
2	6	36	0.2	0.89	0	1	1.1	1	2	1	1	0	0	0	0	5	12	30	30	30	30	21	17	0.19	0.00	1	9	7	1	0	0	0	0	0	1	1	0	1	4
2	6	37	0.2	0.89	0	4	3.3	3	5	1	1	1	1	1	0	1	1	7	15	16	30	19	20	0.50	0.00	3	19	1	0	0	1	1	1	0	1	0	1	1	6
2	6	38	0.2	0.89	0	2	1.1	1	3	1	1	1	0	0	0	8	15	19	30	30	30	18	1	0.03	0.00	1	1	-2	0	0	1	1	0	0	1	0	0	0	3
2	6	48	0.2	0.89	0	2	1.2	1	2	1	1	0	0	0	0	2	21	30	30	30	30	22	29	0.17	0.00	3	9	20	1	0	0	1	0	0	0	0	1	1	4
3	1	1	0.2	0.89	100	6	4.3	5.5	6	1	1	1	1	1	1	2	6	9	12	13	16	21	5	0.00	0.00	0	1	3	0	1	1	1	0	1	1	1	1	0	7
3	1	2	0.2	0.89	100	6	4.3	4	6	1	1	1	1	1	1	1	4	7	10	17	18	21	36	0.42	0.00	1	19	17	1	1	1	1	1	1	0	1	1	1	9
3	1	3	0.2	0.89	100	5	1.7	1	5	1	1	1	1	1	0	15	18	18	25	28	30	20	3	0.00	0.00	0	2	-1	0	0	1	1	0	1	0	0	1	0	4
3	1	4	0.2	0.89	100	6	4.4	6	6	1	1	1	1	1	1	5	8	9	9	11	13	20	9	0.31	0.14	2	-1	9	0	1	1	1	0	0	1	1	1	0	6
3	1	5	0.2	0.89	100	4	1.6	1.5	4	1	1	1	1	0	0	7	16	22	30	30	30	23	6	0.15	0.00	0	6	0	1	0	1	1	0	0	1	1	0	0	5
3	1	6	0.2	0.89	100	6	3.7	3	6	1	1	1	1	1	1	1	2	9	17	20	25	19	4	0.00	0.00	1	4	-1	0	0	1	1	0	1	0	1	1	0	5
3	1	7	0.2	0.89	100	2	1.5	2	2	1	1	0	0	0	0	3	9	30	30	30	30	21	18	0.03	0.00	3	12	5	0	1	0	1	0	1	0	1	1	1	6
3	1	8	0.2	0.89	100	2	1.2	1	2	1	1	0	0	0	0	5	19	30	30	30	30	21	18	0.00	0.00	0	10	7	0	0	0	0	0	1	1	1	0	1	4
3	1	9	0.2	0.89	100	2	1.3	2	2	1	1	0	0	0	0	1	15	30	30	30	30	25	4	0.00	0.00	1	0	2	0	1	0	0	1	0	1	1	1	1	6
3	1	10	0.2	0.89	100	3	1.7	2	4	1	1	1	1	0	0	4	11	12	13	30	30	21	15	0.00	0.00	0	10	5	1	0	1	1	0	1	0	0	1	0	5
3	1	11	0.2	0.89	100	4	1.7	1	5	1	1	1	1	1	0	1	9	23	26	27	30	23	46	0.41	0.00	4	25	22	1	1	1	1	0	1	1	1	1	1	9
3	1	12	0.2	0.89	100	2	1.6	2	3	1	1	1	0	0	0	3	8	25	30	30	30	20	6	0.08	0.00	0	3	2	0	0	1	1	1	0	1	1	0	1	6
3	1	13	0.2	0.89	100	0	0.2	0	1	1	0	0	0	0	0	17	30	30	30	30	30	22	4	0.00	0.00	0	4	0	0	0	0	0	0	0	0	0	1	0	1
3	1	14	0.2	0.89	100	6	5.5	6	6	1	1	1	1	1	1	1	1	1	4	4	8	22	7	0.00	0.00	0	4	2	1	0	1	1	0	0	0	1	1	1	6

3	1	15	0.2	0.89	100	6	3.1	3	6	1	1	1	1	1	1	5	12	15	17	22	23	21	-1	0.00	0.00	0	-1	-1	1	1	1	1	0	0	0	1	0	0	5
3	1	16	0.2	0.89	100	1	0.9	1	2	1	1	0	0	0	0	1	29	30	30	30	30	22	6	0.18	0.00	0	2	2	1	0	0	0	0	0	1	0	0	0	2
3	1	17	0.2	0.89	100	3	1.9	2	3	1	1	1	0	0	0	4	7	14	30	30	30	22	20	0.14	0.00	1	16	3	1	0	1	1	0	0	1	1	1	1	7
3	1	18	0.2	0.89	100	2	1.8	2	3	1	1	1	0	0	0	4	9	18	30	30	30	21	6	0.09	0.00	0	4	1	1	0	1	1	0	0	0	1	1	1	6
3	1	19	0.2	0.89	100	5	3.9	5	5	1	1	1	1	1	0	1	4	9	10	15	30	20	1	0.00	0.00	1	1	-2	0	1	1	1	1	0	1	1	0	1	7
3	1	20	0.2	0.89	100	3	1.0	1	3	1	1	1	0	0	0	14	23	26	30	30	30	19	0	0.00	0.00	0	0	-2	0	1	1	1	0	0	1	1	0	1	6
3	2	21	0.2	0.89	50	0	0.3	0	1	1	0	0	0	0	0	3	30	30	30	30	30	22	15	0.00	0.00	3	3	11	0	1	0	0	0	1	0	0	1	0	3
3	2	22	0.2	0.89	50	3	1.5	1	3	1	1	1	0	0	0	2	18	27	30	30	30	22	7	0.00	0.00	0	6	0	1	1	0	1	0	1	0	0	0	1	5
3	2	23	0.2	0.89	50	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	13	0.00	0.00	1	10	2	0	0	0	0	0	0	0	0	0	0	0
3	2	24	0.2	0.89	50	0	0.4	0	1	1	0	0	0	0	0	7	30	30	30	30	30	25	21	0.21	0.00	3	10	11	1	0	0	0	0	0	0	0	0	1	2
3	2	25	0.2	0.89	50	0	0.7	1	1	1	0	0	0	0	0	1	30	30	30	30	30	19	2	0.17	0.00	0	0	0	1	0	0	0	1	0	1	0	0	0	3
3	2	26	0.2	0.89	50	0	0.2	0	1	1	0	0	0	0	0	15	30	30	30	30	30	20	-2	0.00	0.00	0	-2	-2	1	0	0	0	0	0	0	0	1	0	2
3	2	27	0.2	0.89	50	6	4.4	5	6	1	1	1	1	1	1	3	5	7	9	13	18	21	10	0.08	0.04	1	10	-2	0	0	1	1	1	0	1	0	1	1	6
3	2	28	0.2	0.89	50	2	1.6	2	2	1	1	0	0	0	0	4	9	30	30	30	30	20	7	0.06	0.00	0	5	0	1	0	0	1	1	0	0	0	0	1	4
3	2	29	0.2	0.89	50	3	1.4	1	3	1	1	1	0	0	0	1	11	26	30	30	30	23	5	0.10	0.00	0	3	1	1	1	1	1	1	0	0	1	0	1	7
3	2	30	0.2	0.89	50	2	1.3	1	2	1	1	0	0	0	0	1	4	30	30	30	30	25	31	0.29	0.00	0	20	10	0	1	1	1	0	1	1	1	1	1	8
3	2	31	0.2	0.89	50	1	0.9	1	2	1	1	0	0	0	0	6	24	30	30	30	30	26	0	0.00	0.00	0	0	-2	1	0	0	1	0	1	0	0	0	0	3
3	2	32	0.2	0.89	50	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	21	1	0.00	0.00	0	1	-2	0	0	0	0	0	0	0	0	0	0	0
3	2	33	0.2	0.89	50	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	-2	0.00	0.00	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0
3	2	34	0.2	0.89	50	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	19	3	0.05	0.00	0	1	0	1	0	0	0	0	1	0	1	0	1	4
3	2	35	0.2	0.89	50	2	1.5	2	2	1	1	0	0	0	0	5	13	30	30	30	30	21	4	0.00	0.00	0	4	-2	1	0	0	0	0	0	0	0	1	1	3
3	2	36	0.2	0.89	50	3	2.1	2	3	1	1	1	0	0	0	1	8	14	30	30	30	24	35	0.21	0.17	2	11	24	0	1	1	1	0	1	0	1	1	1	7
3	2	37	0.2	0.89	50	2	1.6	2	2	1	1	0	0	0	0	4	11	30	30	30	30	19	18	0.04	0.00	0	10	7	1	0	0	0	0	1	1	1	1	1	6
3	2	38	0.2	0.89	50	3	2.8	3	4	1	1	1	1	0	0	1	4	7	15	30	30	18	7	0.10	0.00	0	6	0	1	1	1	1	0	0	0	0	1	0	5
3	2	39	0.2	0.89	50	2	0.9	1	2	1	1	0	0	0	0	15	20	30	30	30	30	18	2	0.13	0.00	0	2	-2	1	0	0	0	1	0	1	1	0	1	5
3	2	40	0.2	0.89	50	2	1.5	2	3	1	1	1	0	0	0	5	13	27	30	30	30	21	38	0.31	0.11	2	24	13	0	0	1	1	1	0	1	0	1	1	6
4	1	41	0.16	0.71	100	1	0.4	0	1	1	0	0	0	0	0	19	30	30	30	30	30	21	2	0.00	0.00	0	2	-1	0	0	0	0	0	0	0	1	0	1	2
4	1	42	0.16	0.71	100	2	1.8	2	3	1	1	1	0	0	0	2	12	16	30	30	30	20	1	0.00	0.00	1	1	-2	0	0	1	1	0	1	0	0	0	1	4
4	1	43	0.16	0.71	100	6	4.8	6	6	1	1	1	1	1	1	1	1	9	10	11	11	20	14	0.32	0.00	0	3	11	0	1	1	1	0	1	0	1	1	0	6
4	1	44	0.16	0.71	100	0	0.1	0	1	1	0	0	0	0	0	17	30	30	30	30	30	22	7	0.00	0.00	3	3	3	1	0	0	0	0	0	1	0	0	0	2
4	1	45	0.16	0.71	100	2	1.3	1	2	1	1	0	0	0	0	4	17	30	30	30	30	19	10	0.21	0.00	0	10	-1	1	0	0	1	0	0	1	0	1	1	5
4	1	46	0.16	0.71	100	1	0.9	1	1	1	0	0	0	0	0	1	30	30	30	30	30	21	27	0.00	0.00	1	20	6	0	0	0	0	1	0	1	0	1	0	3
4	1	47	0.16	0.71	100	2	2.0	2	3	1	1	1	0	0	0	2	6	18	30	30	30	24	13	0.11	0.00	0	9	4	1	1	1	1	0	0	1	0	1	1	7

4	1	48	0.16	0.71	100	4	1.9	2	4	1	1	1	1	0	0	6	11	24	27	30	30	19	6	0.00	0.00	0	1	3	1	0	1	1	1	1	1	1	0	1	8
4	1	49	0.16	0.71	100	5	2.7	3	5	1	1	1	1	1	0	3	8	14	21	28	30	20	14	0.58	0.00	1	14	0	0	0	1	1	1	0	1	1	1	1	7
4	1	50	0.16	0.71	100	3	0.8	1	3	1	1	1	0	0	0	12	26	30	30	30	30	23	5	0.00	0.00	0	3	0	0	0	0	1	0	0	0	1	1	0	3
4	1	51	0.16	0.71	100	1	0.4	0	1	1	0	0	0	0	0	13	30	30	30	30	30	18	1	0.00	0.00	1	1	-1	1	0	0	0	0	0	0	0	0	1	2
4	1	52	0.16	0.71	100	3	1.8	2	3	1	1	1	0	0	0	5	13	20	30	30	30	18	11	0.10	0.00	1	11	-1	1	0	1	1	1	0	1	1	1	1	8
4	1	53	0.16	0.71	100	3	1.6	2	3	1	1	1	0	0	0	7	11	28	30	30	30	20	4	0.00	0.00	0	4	-2	1	1	1	0	1	1	1	1	1	0	8
4	1	54	0.16	0.71	100	6	3.8	5	6	1	1	1	1	1	1	4	10	12	13	15	17	19	14	0.15	0.00	1	11	2	1	1	1	1	1	0	0	1	1	0	7
4	1	55	0.16	0.71	100	3	1.7	2	3	1	1	1	0	0	0	6	14	21	30	30	30	19	1	0.00	0.00	0	1	-1	1	0	1	1	1	0	1	1	0	1	7
4	1	56	0.16	0.71	100	6	4.2	5	6	1	1	1	1	1	1	1	3	8	14	15	18	19	24	0.40	0.00	0	21	4	1	1	1	1	0	1	1	1	1	1	9
4	1	57	0.16	0.71	100	6	5.1	6	6	1	1	1	1	1	1	1	4	5	6	8	8	19	7	0.00	0.00	1	0	5	0	1	1	1	1	0	0	1	1	0	6
4	1	58	0.16	0.71	100	2	0.4	0	2	1	1	0	0	0	0	21	28	30	30	30	30	24	3	0.00	0.00	0	1	2	0	0	0	1	0	0	1	0	0	0	2
4	1	59	0.16	0.71	100	2	1.5	2	2	1	1	0	0	0	0	1	15	30	30	30	30	22	1	0.00	0.00	0	0	1	1	1	0	0	1	0	1	1	1	0	6
4	1	60	0.16	0.71	100	2	0.6	1	2	1	1	0	0	0	0	15	21	30	30	30	30	24	6	0.00	0.00	0	1	3	1	0	0	1	0	0	1	0	0	0	3
4	2	61	0.125	0.56	100	6	3.7	4.5	6	1	1	1	1	1	1	5	8	13	15	16	18	18	-1	0.00	0.00	0	-1	-1	0	1	1	0	0	0	1	1	1	1	6
4	2	62	0.125	0.56	100	2	1.5	1.5	2	1	1	0	0	0	0	1	14	30	30	30	30	24	16	0.24	0.00	0	13	3	1	0	0	0	0	0	0	1	0	1	3
4	2	63	0.125	0.56	100	2	1.0	1	2	1	1	0	0	0	0	14	18	30	30	30	30	22	0	0.00	0.00	2	-2	0	1	0	0	1	0	0	0	0	0	0	2
4	2	64	0.125	0.56	100	1	1.2	1	2	1	1	0	0	0	0	8	14	30	30	30	30	21	18	0.11	0.00	2	5	12	1	1	0	1	0	0	0	1	0	1	5
4	2	65	0.125	0.56	100	1	0.6	0	2	1	1	0	0	0	0	6	26	30	30	30	30	21	10	0.00	0.00	3	8	2	0	0	0	1	0	0	0	1	0	1	3
4	2	66	0.125	0.56	100	1	0.4	0	1	1	0	0	0	0	0	17	30	30	30	30	30	21	11	0.00	0.00	0	7	2	1	0	0	0	0	0	1	0	0	1	3
4	2	67	0.125	0.56	100	1	0.5	0	1	1	0	0	0	0	0	4	30	30	30	30	30	21	3	0.00	0.00	0	3	-1	1	0	0	1	0	0	0	0	0	1	3
4	2	68	0.125	0.56	100	1	1.1	1	2	1	1	0	0	0	0	1	6	30	30	30	30	20	7	0.00	0.00	0	5	1	1	1	0	1	1	0	0	0	0	0	4
4	2	69	0.125	0.56	100	2	0.8	1	2	1	1	0	0	0	0	10	28	30	30	30	30	21	2	0.06	0.00	0	0	0	1	0	0	0	0	0	0	0	1	1	3
4	2	70	0.125	0.56	100	6	3.5	4	6	1	1	1	1	1	1	2	8	13	15	17	23	22	34	0.39	0.00	1	29	6	0	1	1	1	1	0	0	1	1	0	6
4	2	71	0.125	0.56	100	2	1.3	1	3	1	1	1	0	0	0	7	18	27	30	30	30	21	55	0.59	0.11	2	31	23	1	0	1	1	1	0	1	1	1	1	8
4	2	72	0.125	0.56	100	0	0.1	0	1	1	0	0	0	0	0	13	30	30	30	30	30	21	4	0.14	0.00	1	3	-1	1	0	0	0	0	1	0	0	0	1	3
4	2	73	0.125	0.56	100	2	1.5	2	2	1	1	0	0	0	0	5	13	30	30	30	30	21	5	0.00	0.00	0	2	1	1	0	0	1	0	0	0	0	1	1	4
4	2	74	0.125	0.56	100	1	0.5	0.5	2	1	1	0	0	0	0	3	14	30	30	30	30	25	14	0.25	0.00	4	5	9	0	0	0	1	0	1	1	0	0	0	3
4	2	75	0.125	0.56	100	1	0.8	1	2	1	1	0	0	0	0	8	19	30	30	30	30	20	14	0.14	0.00	0	8	5	1	0	1	1	1	0	1	1	0	1	7
4	2	76	0.125	0.56	100	1	0.8	1	1	1	0	0	0	0	0	5	30	30	30	30	30	21	12	0.06	0.00	3	11	0	1	0	0	0	0	1	1	0	0	0	3
4	2	77	0.125	0.56	100	0	0.9	1	2	1	1	0	0	0	0	10	13	30	30	30	30	21	3	0.06	0.00	0	2	0	1	0	0	1	0	0	0	1	1	0	4
4	2	78	0.125	0.56	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	2	0.05	0.00	1	1	0	1	0	0	0	0	0	0	0	1	1	3
4	2	79	0.125	0.56	100	3	1.4	2	3	1	1	1	0	0	0	8	12	29	30	30	30	20	42	0.12	0.00	4	19	24	0	0	1	1	1	1	1	1	1	1	8
4	2	96	0.125	0.56	100	1	0.2	0	1	1	0	0	0	0	0	6	30	30	30	30	30	19	12	0.13	0.00	1	7	4	0	1	0	0	1	0	0	0	0	0	2

4	3	1	0.08	0.36	100	4	2.5	3	4	1	1	1	1	0	0	2	5	12	29	30	30	19	36	0.50	0.00	2	24	13	0	1	1	0	1	0	1	1	1	0	6
4	3	2	0.08	0.36	100	0	0.1	0	1	1	0	0	0	0	0	11	30	30	30	30	30	20	15	0.05	0.05	2	3	10	0	0	0	0	0	0	0	1	0	0	1
4	3	3	0.08	0.36	100	4	2.7	3	4	1	1	1	1	0	0	5	8	11	15	30	30	20	5	0.29	0.00	0	5	-1	0	0	1	1	0	0	0	1	1	0	4
4	3	4	0.08	0.36	100	1	0.2	0	1	1	0	0	0	0	0	23	30	30	30	30	30	25	8	0.00	0.00	2	3	4	0	0	0	1	0	0	1	0	0	1	3
4	3	5	0.08	0.36	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	21	1	0.00	0.00	0	-2	1	1	0	0	0	0	1	0	0	0	0	2
4	3	6	0.08	0.36	100	2	1.1	1	2	1	1	0	0	0	0	6	20	30	30	30	30	24	7	0.00	0.00	1	5	2	0	0	0	0	1	0	1	0	1	1	4
4	3	7	0.08	0.36	100	0	0.5	0	2	1	1	0	0	0	0	7	8	30	30	30	30	18	1	0.00	0.00	0	1	0	1	0	0	1	0	1	0	0	0	1	4
4	3	8	0.08	0.36	100	2	1.5	2	2	1	1	0	0	0	0	4	12	30	30	30	30	19	6	0.00	0.00	0	5	-1	1	0	0	0	1	0	1	1	0	1	5
4	3	9	0.08	0.36	100	4	2.1	2	4	1	1	1	1	0	0	5	14	19	22	30	30	22	43	0.27	0.00	2	36	8	0	0	1	1	1	0	0	0	1	0	4
4	3	10	0.08	0.36	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	24	17	0.00	0.00	2	7	8	1	0	0	0	0	1	0	1	0	1	4
4	3	11	0.08	0.36	100	6	5.0	6	6	1	1	1	1	1	1	2	2	5	8	10	10	22	12	0.00	0.00	2	4	8	0	1	1	1	1	0	0	1	1	1	7
4	3	12	0.08	0.36	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	23	-1	0.00	0.00	0	-2	-1	1	0	0	0	0	0	0	0	0	0	1
4	3	13	0.08	0.36	100	2	1.4	2	2	1	1	0	0	0	0	8	11	30	30	30	30	19	27	0.00	0.00	0	4	22	1	0	0	1	0	0	0	0	0	1	3
4	3	14	0.08	0.36	100	1	1.7	2	3	1	1	1	0	0	0	1	5	19	30	30	30	26	15	0.25	0.00	2	11	4	1	1	1	1	0	1	0	1	0	1	7
4	3	15	0.08	0.36	100	3	2.0	3	3	1	1	1	0	0	0	5	12	15	30	30	30	19	12	0.00	0.00	0	5	6	0	1	1	0	0	0	0	1	0	0	3
4	3	16	0.08	0.36	100	3	2.3	2	3	1	1	1	0	0	0	1	6	15	30	30	30	18	11	0.38	0.00	0	4	7	1	0	1	1	1	0	1	0	1	1	7
4	3	17	0.08	0.36	100	2	0.4	0	2	1	1	0	0	0	0	16	29	30	30	30	30	19	3	0.00	0.00	0	-2	3	0	0	0	0	0	1	1	0	1	1	4
4	3	18	0.08	0.36	100	0	0.4	0	1	1	0	0	0	0	0	5	30	30	30	30	30	21	8	0.04	0.00	1	7	1	0	1	0	0	0	0	0	0	0	1	2
4	3	19	0.08	0.36	100	2	1.6	2	2	1	1	0	0	0	0	4	9	30	30	30	30	20	38	0.44	0.00	3	24	14	1	0	0	1	0	1	1	0	1	1	6
4	3	20	0.08	0.36	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	1	0.00	0.00	0	1	1	0	0	0	0	0	0	0	0	0	0	0
4	4	21	0.05	0.22	100	1	0.7	1	1	1	0	0	0	0	0	11	30	30	30	30	30	25	2	0.00	0.00	0	0	1	0	1	0	0	0	0	1	0	0	0	2
4	4	22	0.05	0.22	100	4	2.0	2	4	1	1	1	1	0	0	5	9	19	30	30	30	19	2	0.00	0.00	0	2	-1	0	0	1	1	1	1	0	1	1	0	6
4	4	23	0.05	0.22	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	-1	0.00	0.00	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
4	4	24	0.05	0.22	100	4	2.2	2	4	1	1	1	1	0	0	3	10	20	26	30	30	21	92	0.29	0.10	4	35	58	1	1	1	1	0	1	0	1	0	1	7
4	4	25	0.05	0.22	100	1	0.4	0	1	1	0	0	0	0	0	13	30	30	30	30	30	21	4	0.07	0.00	0	4	-1	0	1	0	0	0	1	0	1	0	0	3
4	4	26	0.05	0.22	100	2	1.4	1	2	1	1	0	0	0	0	3	17	30	30	30	30	18	17	0.08	0.00	2	11	4	0	0	0	0	0	1	1	1	0	1	4
4	4	27	0.05	0.22	100	3	2.7	3	4	1	1	1	1	0	0	4	8	10	18	30	30	19	5	0.10	0.00	2	3	0	0	0	1	1	1	1	0	1	0	0	5
4	4	28	0.05	0.22	100	1	0.9	1	1	1	0	0	0	0	0	4	30	30	30	30	30	19	8	0.05	0.00	0	6	1	1	0	0	0	0	0	0	1	0	1	3
4	4	29	0.05	0.22	100	2	1.4	1	2	1	1	0	0	0	0	2	11	30	30	30	30	22	20	0.14	0.00	2	0	19	1	0	0	1	0	1	0	1	0	1	5
4	4	30	0.05	0.22	100	2	1.9	2	3	1	1	1	0	0	0	2	7	23	30	30	30	18	26	0.15	0.00	1	21	5	0	1	1	1	0	1	1	0	0	0	5
4	4	31	0.05	0.22	100	1	0.8	1	1	1	0	0	0	0	0	8	30	30	30	30	30	19	6	0.00	0.00	0	3	1	1	0	0	1	0	0	0	1	0	0	3
4	4	32	0.05	0.22	100	1	0.9	1	1	1	0	0	0	0	0	4	30	30	30	30	30	19	2	0.00	0.00	0	2	-1	0	0	0	1	0	0	0	1	0	0	2
4	4	33	0.05	0.22	100	1	0.6	1	1	1	0	0	0	0	0	5	30	30	30	30	30	19	20	0.00	0.00	0	10	10	1	0	0	0	0	1	0	0	0	1	3

4	4	34	0.05	0.22	100	0	0.8	1	1	1	0	0	0	0	0	4	30	30	30	30	30	22	14	0.24	0.00	1	7	7	1	0	0	1	0	1	0	0	0	0	3
4	4	35	0.05	0.22	100	2	1.5	2	2	1	1	0	0	0	0	5	13	30	30	30	30	18	19	0.12	0.00	1	11	7	1	0	0	1	0	1	0	0	0	1	4
4	4	36	0.05	0.22	100	0	0.3	0	1	1	0	0	0	0	0	7	30	30	30	30	30	20	4	0.00	0.00	0	4	-2	1	0	0	1	0	0	0	0	0	1	3
4	4	37	0.05	0.22	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	7	0.23	0.00	1	7	-1	0	0	0	0	0	0	0	0	0	0	0
4	4	38	0.05	0.22	100	1	0.5	0	1	1	0	0	0	0	0	17	30	30	30	30	30	19	11	0.00	0.00	0	7	3	1	0	0	0	1	1	0	0	0	0	3
4	4	39	0.05	0.22	100	0	0.3	0	1	1	0	0	0	0	0	14	30	30	30	30	30	24	7	0.08	0.00	2	4	3	0	0	0	0	1	0	0	1	0	0	2
4	4	40	0.05	0.22	100	3	2.0	2	3	1	1	1	0	0	0	4	9	21	30	30	30	19	14	0.00	0.00	2	10	3	1	0	1	1	1	0	0	1	0	0	5
4	5	80	0.315	0.70	100	2	1.4	2	2	1	1	0	0	0	0	7	13	30	30	30	30	20	5	0.04	0.00	1	5	0	1	0	0	0	0	0	0	0	0	1	2
4	5	81	0.315	0.70	100	0	0.2	0	1	1	0	0	0	0	0	9	30	30	30	30	30	22	33	0.35	0.00	0	14	20	0	1	0	0	0	0	0	1	0	0	2
4	5	82	0.315	0.70	100	6	4.0	5	6	1	1	1	1	1	1	4	6	9	13	15	20	25	4	0.00	0.00	0	1	4	1	0	1	1	0	0	0	1	0	0	4
4	5	83	0.315	0.70	100	6	5.1	6	6	1	1	1	1	1	1	1	1	3	5	9	14	26	36	0.34	0.00	3	31	6	0	1	1	1	0	1	1	1	1	0	7
4	5	84	0.315	0.70	100	0	1.0	1	2	1	1	0	0	0	0	5	8	30	30	30	30	25	19	0.04	0.00	2	8	9	1	0	0	0	0	0	0	1	0	1	3
4	5	85	0.315	0.70	100	0	0.1	0	1	1	0	0	0	0	0	19	30	30	30	30	30	20	3	0.00	0.00	1	-2	3	1	0	0	0	0	0	0	0	0	1	2
4	5	86	0.315	0.70	100	6	3.3	3	6	1	1	1	1	1	1	1	9	12	19	22	24	21	32	0.43	0.00	4	17	16	1	1	1	1	0	1	1	1	1	1	9
4	5	87	0.315	0.70	100	2	2.1	2	3	1	1	1	0	0	0	3	7	12	30	30	30	23	-1	0.00	0.00	0	-2	-1	1	1	1	1	0	0	0	1	0	1	6
4	5	88	0.315	0.70	100	3	2.0	2	3	1	1	1	0	0	0	5	10	18	30	30	30	25	33	0.00	0.00	1	15	16	0	0	1	0	0	1	0	0	1	1	4
4	5	89	0.315	0.70	100	4	1.8	2	4	1	1	1	1	0	0	3	14	19	30	30	30	20	10	0.00	0.00	0	4	6	0	1	1	1	0	0	1	1	1	1	7
4	5	91	0.315	0.70	100	4	2.5	3	4	1	1	1	1	0	0	5	11	13	19	30	30	20	6	0.33	0.10	0	6	1	1	1	1	1	0	1	0	1	1	1	8
4	5	92	0.315	0.70	100	6	3.5	3.5	6	1	1	1	1	1	1	4	7	10	16	21	24	24	7	0.00	0.00	1	6	0	0	1	1	1	0	1	0	1	1	0	6
4	5	93	0.315	0.70	100	6	3.8	3.5	6	1	1	1	1	1	1	4	8	8	16	17	18	19	6	0.13	0.00	0	2	3	1	1	1	1	1	0	0	0	1	1	7
4	5	94	0.315	0.70	100	4	2.0	3	4	1	1	1	1	0	0	9	11	15	30	30	30	20	3	0.00	0.00	2	1	0	1	0	1	1	0	1	0	0	1	1	6
4	5	97	0.315	0.70	100	5	3.3	4	5	1	1	1	1	1	0	5	7	12	14	16	30	19	22	0.36	0.00	0	16	5	1	1	1	1	1	0	1	0	1	1	8
4	5	99	0.315	0.70	100	1	0.5	1	1	1	0	0	0	0	0	15	30	30	30	30	30	20	-1	0.00	0.00	0	-1	-1	0	0	0	1	0	0	0	1	1	0	3
4	5	100	0.315	0.70	100	3	1.9	2	3	1	1	1	0	0	0	4	11	21	30	30	30	18	17	0.03	0.00	0	9	7	1	1	1	1	1	0	0	1	1	1	8
4	5	101	0.315	0.70	100	1	0.8	1	2	1	1	0	0	0	0	7	14	30	30	30	30	19	5	0.13	0.00	2	5	-2	1	0	0	1	0	1	0	1	0	1	5
4	5	102	0.315	0.70	100	2	1.7	2	2	1	1	0	0	0	0	3	7	30	30	30	30	19	13	0.10	0.00	0	10	3	1	0	0	0	1	0	1	1	1	1	6
4	5	104	0.315	0.70	100	1	0.7	1	1	1	0	0	0	0	0	10	30	30	30	30	30	20	1	0.00	0.00	0	0	1	0	1	0	0	0	0	0	1	0	0	2
4	6	90	0.315	0.70	0	2	1.5	2	2	1	1	0	0	0	0	4	12	30	30	30	30	22	-1	0.00	0.00	0	-1	-1	1	0	0	1	0	0	0	1	1	1	5
4	6	95	0.315	0.70	0	2	1.4	1	2	1	1	0	0	0	0	3	18	30	30	30	30	21	28	0.00	0.00	1	17	10	1	0	0	0	0	0	0	1	1	1	4
4	6	98	0.315	0.70	0	3	2.0	2	3	1	1	1	0	0	0	2	4	28	30	30	30	21	20	0.00	0.00	3	13	6	1	1	1	1	0	0	0	0	0	1	5
4	6	103	0.315	0.70	0	1	0.4	0	1	1	0	0	0	0	0	19	30	30	30	30	30	23	4	0.00	0.00	0	1	1	0	0	0	0	0	0	0	0	1	1	1
4	6	105	0.315	0.70	0	1	0.5	0.5	1	1	0	0	0	0	0	5	30	30	30	30	30	23	-1	0.00	0.00	0	-2	-1	0	0	0	0	1	0	0	0	0	0	1
4	6	106	0.315	0.70	0	2	1.1	1	2	1	1	0	0	0	0	9	20	30	30	30	30	19	5	0.00	0.00	1	2	2	0	1	0	0	0	0	1	0	0	0	2

4	6	107	0.315	0.70	0	2	1.2	1.5	2	1	1	0	0	0	0	10	16	30	30	30	30	22	8	0.00	0.00	1	5	2	1	0	0	0	0	0	0	0	1	1	3
4	6	108	0.315	0.70	0	2	1.8	2	3	1	1	1	0	0	0	2	8	15	30	30	30	19	29	0.00	0.00	4	15	12	1	0	1	0	1	1	1	0	0	1	6
4	6	109	0.315	0.70	0	0	0.4	0	1	1	0	0	0	0	0	1	30	30	30	30	30	24	8	0.04	0.00	0	4	3	1	0	0	0	1	0	0	0	0	1	3
4	6	110	0.315	0.70	0	1	0.8	1	1	1	0	0	0	0	0	6	30	30	30	30	30	21	1	0.00	0.00	0	0	-1	0	0	0	0	0	0	1	0	1	1	3
4	6	111	0.315	0.70	0	2	1.0	1	2	1	1	0	0	0	0	6	23	30	30	30	30	22	8	0.06	0.00	0	5	2	0	1	0	0	1	0	0	1	1	0	4
4	6	112	0.315	0.70	0	1	0.6	1	1	1	0	0	0	0	0	4	30	30	30	30	30	20	4	0.07	0.00	0	4	-1	0	0	0	0	0	0	0	0	1	0	1
4	6	113	0.315	0.70	0	2	1.2	1	2	1	1	0	0	0	0	5	21	30	30	30	30	20	4	0.00	0.00	0	2	1	0	1	0	0	1	0	0	1	0	1	4
4	6	114	0.315	0.70	0	1	0.6	1	1	1	0	0	0	0	0	12	30	30	30	30	30	19	6	0.05	0.00	0	2	3	1	0	0	0	0	0	0	0	0	1	2
4	6	115	0.315	0.70	0	3	1.7	2	3	1	1	1	0	0	0	5	10	24	30	30	30	20	2	0.00	0.00	1	2	-2	1	1	1	1	0	0	0	1	0	0	5
4	6	116	0.315	0.70	0	1	0.8	1	2	1	1	0	0	0	0	5	17	30	30	30	30	21	13	0.15	0.00	2	8	3	1	0	0	0	0	0	0	0	0	1	2
4	6	117	0.315	0.70	0	6	4.3	5	6	1	1	1	1	1	1	1	3	8	11	13	20	26	13	0.00	0.00	2	7	4	1	0	1	1	0	1	1	0	1	1	7
4	6	118	0.315	0.70	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	-1	0.00	0.00	0	-1	-1	0	0	0	0	0	1	0	0	0	0	1
4	6	119	0.315	0.70	0	0	0.0	0	1	1	0	0	0	0	0	13	30	30	30	30	30	21	6	0.00	0.00	0	4	3	0	0	0	1	0	0	0	0	0	0	1
4	6	120	0.315	0.70	0	0	0.3	0	1	1	0	0	0	0	0	6	30	30	30	30	30	22	1	0.00	0.00	0	0	-1	0	0	0	0	0	0	0	1	0	0	1
5	1	1	0.1	0.89	0	1	0.7	1	1	1	0	0	0	0	0	11	30	30	30	30	30	19	-2	0.00	0.00	0	-2	-2	0	0	0	0	0	0	1	1	0	0	2
5	1	2	0.1	0.89	0	1	1.1	1	2	1	1	0	0	0	0	2	20	30	30	30	30	21	13	0.11	0.00	0	8	4	1	0	0	1	1	0	0	1	0	1	5
5	1	3	0.1	0.89	0	2	1.3	1	2	1	1	0	0	0	0	2	13	30	30	30	30	18	9	0.13	0.00	1	9	-2	1	0	0	1	0	0	1	1	1	1	6
5	1	4	0.1	0.89	0	0	0.4	0	1	1	0	0	0	0	0	2	30	30	30	30	30	20	19	0.20	0.00	1	12	5	1	0	0	0	0	0	0	1	1	1	4
5	1	5	0.1	0.89	0	2	1.2	1	2	1	1	0	0	0	0	6	20	30	30	30	30	20	34	0.58	0.10	4	13	20	1	1	0	1	0	1	1	1	1	1	8
5	1	6	0.1	0.89	0	0	0.4	0	2	1	1	0	0	0	0	10	12	30	30	30	30	22	5	0.06	0.00	2	5	-2	0	0	0	0	0	0	0	1	0	1	2
5	1	7	0.1	0.89	0	2	1.3	1	2	1	1	0	0	0	0	5	18	30	30	30	30	18	1	0.00	0.00	0	1	-1	0	0	0	0	0	1	1	1	0	1	4
5	1	8	0.1	0.89	0	1	1.5	2	2	1	1	0	0	0	0	3	12	30	30	30	30	19	7	0.00	0.00	4	4	1	1	0	0	0	0	0	0	1	1	1	4
5	1	9	0.1	0.89	0	1	0.3	0	1	1	0	0	0	0	0	21	30	30	30	30	30	22	14	0.19	0.00	2	10	4	1	0	0	0	0	0	0	0	1	1	3
5	1	10	0.1	0.89	0	6	4.4	5	6	1	1	1	1	1	1	4	5	7	10	12	17	19	20	0.21	0.00	3	18	2	0	1	1	1	0	1	1	1	1	1	8
5	1	11	0.1	0.89	0	0	0.3	0	1	1	0	0	0	0	0	7	30	30	30	30	30	19	2	0.00	0.00	0	-2	2	0	0	0	0	0	1	0	1	0	0	2
5	1	12	0.1	0.89	0	3	2.0	2	3	1	1	1	0	0	0	3	9	20	30	30	30	18	3	0.00	0.00	0	2	-1	0	0	1	1	0	0	0	1	1	0	4
5	1	13	0.1	0.89	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	10	0.00	0.00	0	6	3	1	0	0	0	0	0	0	0	0	0	1
5	1	14	0.1	0.89	0	4	2.0	2	4	1	1	1	1	0	0	4	15	19	27	30	30	22	27	0.00	0.00	3	20	7	1	1	0	1	0	0	0	1	1	1	6
5	1	15	0.1	0.89	0	1	0.9	1	1	1	0	0	0	0	0	5	30	30	30	30	30	23	12	0.00	0.00	0	6	5	1	0	0	0	0	0	0	1	0	0	2
5	1	16	0.1	0.89	0	0	0.1	0	1	1	0	0	0	0	0	12	30	30	30	30	30	21	11	0.17	0.00	2	4	6	1	1	0	1	0	0	0	0	0	0	3
5	1	17	0.1	0.89	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	18	-1	0.00	0.00	0	-1	-2	0	0	0	0	1	0	0	0	0	0	1
5	1	18	0.1	0.89	0	3	1.2	1	3	1	1	1	0	0	0	1	9	28	30	30	30	21	10	0.00	0.00	2	7	1	0	0	1	1	0	1	0	1	1	1	6
5	1	19	0.1	0.89	0	1	0.9	1	2	1	1	0	0	0	0	7	14	30	30	30	30	21	6	0.00	0.00	0	6	-2	1	0	0	1	0	0	0	1	0	1	4

5	1	20	0.1	0.89	0	0	0.4	0	1	1	0	0	0	0	0	3	30	30	30	30	30	26	15	0.40	0.00	4	3	11	0	0	1	0	0	0	1	0	0	1	3
5	2	81	0.1	0.89	25	0	0.3	0	2	1	1	0	0	0	0	19	24	30	30	30	30	20	20	0.10	0.00	3	10	10	1	0	0	1	0	0	1	1	1	1	6
5	2	82	0.1	0.89	25	1	0.5	0.5	1	1	0	0	0	0	0	16	30	30	30	30	30	22	4	0.14	0.00	1	-1	4	0	0	0	0	0	0	0	0	0	1	1
5	2	83	0.1	0.89	25	2	1.2	1	2	1	1	0	0	0	0	9	18	30	30	30	30	21	20	0.17	0.00	0	17	2	0	0	0	1	0	0	0	1	0	1	3
5	2	84	0.1	0.89	25	0	0.3	0	1	1	0	0	0	0	0	9	30	30	30	30	30	21	6	0.00	0.00	2	1	3	1	0	0	0	0	0	0	1	0	1	3
5	2	85	0.1	0.89	25	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	-1	0.00	0.00	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
5	2	86	0.1	0.89	25	0	0.5	0.5	1	1	0	0	0	0	0	6	30	30	30	30	30	22	14	0.08	0.00	0	10	3	1	1	0	0	1	0	0	1	1	0	5
5	2	87	0.1	0.89	25	1	0.7	1	1	1	0	0	0	0	0	11	30	30	30	30	30	21	5	0.00	0.00	0	4	0	1	0	0	0	0	0	0	1	0	1	3
5	2	88	0.1	0.89	25	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	19	0	0.04	0.00	0	0	-2	1	0	0	0	0	0	0	0	0	0	1
5	2	89	0.1	0.89	25	3	1.9	2	3	1	1	1	0	0	0	3	10	22	30	30	30	22	-2	0.00	0.00	0	-2	-2	0	0	0	1	1	0	1	0	1	1	5
5	2	90	0.1	0.89	25	2	1.6	2	3	1	1	1	0	0	0	1	4	3	30	30	30	19	5	0.00	0.00	0	4	0	1	1	1	1	1	1	1	1	1	1	10
5	2	91	0.1	0.89	25	2	1.7	2	2	1	1	0	0	0	0	3	9	30	30	30	30	19	4	0.21	0.00	1	3	0	0	0	0	1	1	0	1	1	1	0	5
5	2	92	0.1	0.89	25	0	0.3	0	1	1	0	0	0	0	0	10	30	30	30	30	30	19	17	0.08	0.03	1	9	8	1	0	0	1	1	1	0	1	0	1	6
5	2	93	0.1	0.89	25	1	0.1	0	1	1	0	0	0	0	0	28	30	30	30	30	30	18	-1	0.00	0.00	0	-2	-1	0	0	0	0	0	0	0	0	0	1	1
5	2	94	0.1	0.89	25	2	1.6	2	2	1	1	0	0	0	0	3	11	30	30	30	30	23	19	0.43	0.00	0	14	4	1	0	1	0	0	0	0	0	0	1	3
5	2	95	0.1	0.89	25	2	0.6	1	2	1	1	0	0	0	0	13	18	30	30	30	30	19	0	0.00	0.00	0	0	-1	0	0	0	0	1	1	1	1	0	0	4
5	2	96	0.1	0.89	25	2	1.6	2	4	1	1	1	1	0	0	11	14	19	27	30	30	19	22	0.00	0.00	0	17	5	1	0	1	1	0	0	1	1	1	1	7
5	2	97	0.1	0.89	25	0	0.2	0	1	1	0	0	0	0	0	18	30	30	30	30	30	19	1	0.04	0.00	0	0	-1	1	0	0	1	0	0	0	0	0	1	3
5	2	98	0.1	0.89	25	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	26	2	0.00	0.00	0	2	-1	0	0	0	0	0	0	0	0	0	0	0
5	2	99	0.1	0.89	25	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	21	1	0.00	0.00	1	1	-2	1	0	0	0	0	1	0	0	0	0	2
5	2	100	0.1	0.89	25	2	0.6	1	2	1	1	0	0	0	0	15	28	30	30	30	30	20	10	0.00	0.00	2	6	2	1	0	0	1	0	0	1	0	0	1	4
5	3	38	0.1	0.89	50	2	1.4	2	2	1	1	0	0	0	0	4	15	30	30	30	30	22	18	0.00	0.00	4	11	6	0	0	0	0	0	1	0	1	1	1	4
5	3	39	0.1	0.89	50	2	1.4	1	2	1	1	0	0	0	0	1	20	30	30	30	30	22	24	0.18	0.03	3	19	4	1	1	0	1	0	0	0	1	0	1	5
5	3	40	0.1	0.89	50	2	1.5	2	2	1	1	0	0	0	0	4	9	30	30	30	30	21	15	0.03	0.00	3	4	10	0	0	0	0	1	0	1	1	1	1	5
5	3	41	0.1	0.89	50	1	0.4	0	1	1	0	0	0	0	0	4	30	30	30	30	30	22	4	0.00	0.00	0	2	0	0	0	0	0	0	0	0	1	0	1	2
5	3	42	0.1	0.89	50	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	26	0	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	3	44	0.1	0.89	50	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	5	0.00	0.00	1	3	1	0	0	0	0	0	0	0	0	0	1	1
5	3	45	0.1	0.89	50	5	2.5	2.5	5	1	1	1	1	1	0	8	12	16	19	26	30	18	44	0.26	0.00	3	23	21	1	1	1	0	1	1	1	1	0	1	8
5	3	46	0.1	0.89	50	0	0.6	1	1	1	0	0	0	0	0	2	30	30	30	30	30	19	0	0.00	0.00	0	0	-1	1	0	0	1	0	1	0	0	0	1	4
5	3	47	0.1	0.89	50	1	0.9	1	2	1	1	0	0	0	0	3	11	30	30	30	30	19	3	0.00	0.00	0	3	-1	1	0	0	1	0	1	0	0	0	0	3
5	3	48	0.1	0.89	50	5	2.6	2.5	5	1	1	1	1	1	0	4	7	16	23	27	30	19	15	0.00	0.00	3	7	7	1	0	1	1	1	0	0	1	1	1	6
5	3	49	0.1	0.89	50	2	1.1	1	2	1	1	0	0	0	0	4	20	30	30	30	30	21	20	0.10	0.00	0	18	1	0	1	0	1	0	1	0	1	1	1	6
5	3	50	0.1	0.89	50	2	0.3	0	2	1	1	0	0	0	0	26	26	30	30	30	30	19	4	0.00	0.00	0	0	2	0	0	0	0	0	0	0	1	0	0	1

5	3	51	0.1	0.89	50	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	24	19	0.00	0.00	1	7	10	1	0	0	0	0	0	0	0	0	1	2
5	3	52	0.1	0.89	50	1	1.3	1	2	1	1	0	0	0	0	5	11	30	30	30	30	22	5	0.04	0.00	2	3	1	1	0	0	0	1	0	0	1	0	0	3
5	3	53	0.1	0.89	50	2	1.3	1.5	2	1	1	0	0	0	0	7	16	30	30	30	30	20	37	0.00	0.00	0	19	17	1	1	0	0	0	0	0	1	0	1	4
5	3	54	0.1	0.89	50	2	1.8	2	2	1	1	0	0	0	0	2	5	30	30	30	30	22	14	0.20	0.00	2	13	0	1	1	0	0	1	1	1	0	0	0	5
5	3	55	0.1	0.89	50	2	1.3	1	2	1	1	0	0	0	0	1	21	30	30	30	30	18	11	0.04	0.00	2	10	1	1	1	0	1	1	0	1	0	1	1	7
5	3	75	0.1	0.89	50	2	1.4	2	2	1	1	0	0	0	0	8	13	30	30	30	30	23	4	0.10	0.00	0	1	2	0	1	0	0	0	0	1	0	0	1	3
5	3	78	0.1	0.89	50	1	0.2	0	1	1	0	0	0	0	0	24	30	30	30	30	30	20	3	0.00	0.00	0	1	1	0	1	0	0	0	0	0	0	0	0	1
5	3	80	0.1	0.89	50	2	1.2	1.5	2	1	1	0	0	0	0	10	16	30	30	30	30	20	-2	0.00	0.00	0	-2	-2	0	0	0	0	0	0	0	1	0	1	2
5	4	56	0.1	0.89	75	0	0.2	0	1	1	0	0	0	0	0	7	30	30	30	30	30	20	6	0.04	0.00	0	4	0	1	0	0	1	0	0	1	1	0	1	5
5	4	57	0.1	0.89	75	1	0.0	0	1	1	0	0	0	0	0	30	30	30	30	30	30	18	6	0.14	0.00	0	4	1	0	0	0	0	0	0	0	0	0	1	1
5	4	58	0.1	0.89	75	3	1.6	2	3	1	1	1	0	0	0	2	14	24	30	30	30	24	11	0.00	0.00	0	8	1	0	0	1	0	0	0	0	1	1	1	4
5	4	59	0.1	0.89	75	0	0.2	0	1	1	0	0	0	0	0	22	30	30	30	30	30	19	2	0.00	0.00	0	0	2	1	0	0	1	0	0	0	0	0	0	2
5	4	60	0.1	0.89	75	3	2.0	2	3	1	1	1	0	0	0	4	9	20	30	30	30	21	4	0.10	0.00	0	0	3	0	0	1	1	0	1	0	1	1	1	6
5	4	61	0.1	0.89	75	6	4.2	6	6	1	1	1	1	1	1	5	7	10	10	14	15	19	14	0.04	0.00	2	8	4	1	0	1	1	1	0	1	0	0	1	6
5	4	62	0.1	0.89	75	1	0.3	0	1	1	0	0	0	0	0	19	30	30	30	30	30	19	-2	0.00	0.00	0	-2	-2	0	1	0	0	0	0	0	0	1	0	2
5	4	63	0.1	0.89	75	2	1.5	1.5	2	1	1	0	0	0	0	2	12	30	30	30	30	21	10	0.04	0.00	4	5	5	1	0	0	1	0	1	0	0	1	1	5
5	4	65	0.1	0.89	75	3	1.2	1.5	3	1	1	1	0	0	0	11	16	29	30	30	30	21	16	0.00	0.00	0	11	4	1	0	1	1	1	0	0	1	0	1	6
5	4	66	0.1	0.89	75	4	2.3	2	4	1	1	1	1	0	0	5	9	17	21	30	30	21	2	0.00	0.00	0	0	0	1	0	1	0	0	1	1	1	1	1	7
5	4	67	0.1	0.89	75	3	1.5	2	3	1	1	1	0	0	0	6	13	22	30	30	30	22	19	0.30	0.00	3	6	12	1	1	1	1	0	0	0	1	0	1	6
5	4	68	0.1	0.89	75	2	1.6	2	2	1	1	0	0	0	0	3	12	30	30	30	30	21	5	0.00	0.00	0	3	0	1	0	0	1	1	0	1	0	0	1	5
5	4	69	0.1	0.89	75	0	0.2	0	1	1	0	0	0	0	0	6	30	30	30	30	30	19	4	0.06	0.00	1	4	-1	1	0	0	0	1	0	0	0	0	1	3
5	4	71	0.1	0.89	75	1	0.9	1	1	1	0	0	0	0	0	5	30	30	30	30	30	20	2	0.00	0.00	0	-1	2	1	0	0	1	0	0	0	1	0	0	3
5	4	72	0.1	0.89	75	2	0.9	1	2	1	1	0	0	0	0	10	26	30	30	30	30	21	5	0.05	0.05	1	2	2	0	0	0	0	0	0	1	1	1	1	4
5	4	73	0.1	0.89	75	3	3.5	4	5	1	1	1	1	1	0	1	4	5	7	12	30	23	22	0.43	0.00	3	15	6	1	0	1	1	1	0	1	1	0	1	7
5	4	74	0.1	0.89	75	2	1.8	2	2	1	1	0	0	0	0	1	7	30	30	30	30	21	13	0.33	0.00	1	8	5	1	0	0	1	0	0	0	0	1	1	4
5	4	76	0.1	0.89	75	6	3.6	4	6	1	1	1	1	1	1	3	5	9	14	20	27	19	14	0.18	0.00	1	12	1	0	1	1	1	0	1	1	1	1	0	7
5	4	77	0.1	0.89	75	4	2.6	3	4	1	1	1	1	0	0	3	3	12	27	30	30	21	13	0.13	0.00	0	9	4	0	0	1	1	0	0	0	0	0	1	3
5	4	79	0.1	0.89	75	4	2.0	2	4	1	1	1	1	0	0	4	11	20	27	30	30	25	22	0.16	0.00	0	11	10	1	0	1	1	0	1	1	1	1	1	8
5	5	21	0.1	0.89	100	2	2.4	2	3	1	1	1	0	0	0	1	3	12	30	30	30	21	15	0.65	0.00	0	15	-1	1	0	1	1	1	1	1	1	1	1	9
5	5	22	0.1	0.89	100	1	0.6	1	1	1	0	0	0	0	0	2	30	30	30	30	30	20	5	0.00	0.00	0	3	1	0	0	0	1	1	0	0	1	0	1	4
5	5	23	0.1	0.89	100	2	1.6	2	3	1	1	1	0	0	0	2	12	24	30	30	30	18	6	0.04	0.00	0	4	0	0	0	1	1	0	1	0	1	1	1	6
5	5	24	0.1	0.89	100	2	1.6	2	2	1	1	0	0	0	0	3	8	30	30	30	30	26	25	0.00	0.00	3	12	12	1	1	0	1	0	0	0	1	1	1	6
5	5	25	0.1	0.89	100	4	1.9	2	4	1	1	1	1	0	0	1	13	23	29	30	30	20	15	0.06	0.00	2	11	4	1	0	1	1	0	1	0	0	1	1	6

5	5	26	0.1	0.89	100	2	1.3	1	2	1	1	0	0	0	0	3	18	30	30	30	30	21	34	0.00	0.00	1	21	12	0	0	0	0	0	0	0	1	1	1	3
5	5	27	0.1	0.89	100	6	5.0	6	6	1	1	1	1	1	1	1	4	5	7	9	11	20	6	0.00	0.00	1	6	-1	1	0	1	1	0	1	0	0	1	0	5
5	5	28	0.1	0.89	100	0	0.1	0	1	1	0	0	0	0	0	14	30	30	30	30	30	21	-1	0.00	0.00	1	-1	-2	1	0	0	0	0	0	0	1	1	1	4
5	5	29	0.1	0.89	100	6	5.1	6	6	1	1	1	1	1	1	2	1	5	7	8	9	22	19	0.29	0.00	0	9	9	0	0	0	0	1	1	1	1	0	0	4
5	5	30	0.1	0.89	100	2	0.7	0	2	1	1	0	0	0	0	19	22	30	30	30	30	23	4	0.00	0.00	0	1	2	0	1	0	1	0	0	0	1	1	0	4
5	5	31	0.1	0.89	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	18	0	0.00	0.00	0	-2	0	0	0	0	0	0	0	0	0	0	0	0
5	5	32	0.1	0.89	100	2	1.0	1	2	1	1	0	0	0	0	14	17	30	30	30	30	26	2	0.03	0.03	1	2	-2	1	0	0	0	1	0	1	0	0	0	3
5	5	33	0.1	0.89	100	4	1.4	1.5	4	1	1	1	1	0	0	14	16	25	27	30	30	20	4	0.00	0.00	1	4	0	1	0	1	1	1	0	0	1	1	1	7
5	5	34	0.1	0.89	100	0	0.2	0	1	1	0	0	0	0	0	13	30	30	30	30	30	22	3	0.00	0.00	0	-1	2	0	0	0	0	1	0	0	0	0	1	2
5	5	35	0.1	0.89	100	2	1.0	1	2	1	1	0	0	0	0	8	23	30	30	30	30	24	31	0.36	0.00	1	19	12	1	0	0	0	1	0	0	1	0	1	4
5	5	36	0.1	0.89	100	2	0.8	1	2	1	1	0	0	0	0	11	26	30	30	30	30	22	1	0.00	0.00	0	-2	1	1	1	0	1	0	0	0	1	0	1	5
5	5	37	0.1	0.89	100	1	0.3	0	1	1	0	0	0	0	0	16	30	30	30	30	30	18	12	0.03	0.00	0	7	4	1	0	0	0	1	0	0	0	0	0	2
5	5	43	0.1	0.89	100	1	0.7	1	2	1	1	0	0	0	0	10	12	30	30	30	30	19	17	0.00	0.00	3	11	4	0	1	0	1	1	1	1	1	0	1	7
5	5	64	0.1	0.89	100	4	2.8	3	4	1	1	1	1	0	0	2	6	13	19	30	30	18	14	0.07	0.00	3	13	1	1	0	1	1	1	0	1	0	1	1	7
5	5	70	0.1	0.89	100	2	1.7	2	2	1	1	0	0	0	0	2	6	30	30	30	30	18	5	0.10	0.00	1	4	-1	0	1	0	0	1	0	0	1	0	1	4
6	1	1	0.5	0.49	0	3	1.3	1	3	1	1	1	0	0	0	7	14	25	30	30	30	22	11	0.00	0.00	0	7	3	1	0	1	0	0	1	1	0	1	1	6
6	1	2	0.5	0.49	0	0	0.6	1	1	1	0	0	0	0	0	1	30	30	30	30	30	19	16	0.00	0.00	0	8	6	1	0	0	1	0	0	0	1	0	1	4
6	1	3	0.5	0.49	0	1	0.1	0	1	1	0	0	0	0	0	2	30	30	30	30	30	25	0	0.00	0.00	0	0	-1	0	0	0	0	1	0	0	0	0	0	1
6	1	4	0.5	0.49	0	0	0.6	1	1	1	0	0	0	0	0	6	30	30	30	30	30	20	15	0.09	0.00	0	11	4	1	0	0	1	0	0	0	0	0	1	3
6	1	5	0.5	0.49	0	6	4.1	5	6	1	1	1	1	1	1	6	7	9	11	14	17	21	3	0.00	0.00	0	2	-1	1	1	1	1	1	0	0	1	1	1	8
6	1	11	0.5	0.49	0	2	1.4	1	2	1	1	0	0	0	0	1	10	30	30	30	30	19	20	0.00	0.00	2	4	16	0	0	0	1	1	0	0	1	0	1	4
6	1	12	0.5	0.49	0	0	0.1	0	1	1	0	0	0	0	0	11	30	30	30	30	30	18	0	0.08	0.00	0	0	-1	0	0	0	0	0	0	0	1	0	1	2
6	1	13	0.5	0.49	0	5	2.8	3	5	1	1	1	1	1	0	1	8	13	21	27	30	21	4	0.00	0.00	1	3	0	1	0	1	1	0	0	1	1	1	1	7
6	1	14	0.5	0.49	0	1	0.8	1	2	1	1	0	0	0	0	4	10	30	30	30	30	24	7	0.00	0.00	0	7	-1	1	0	0	0	0	1	0	0	0	1	3
6	1	15	0.5	0.49	0	5	3.5	4	5	1	1	1	1	1	0	3	6	10	13	18	30	22	4	0.00	0.00	0	1	2	1	0	1	1	0	1	0	0	1	1	6
6	1	21	0.5	0.49	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	19	12	0.00	0.00	1	10	1	1	0	0	0	0	0	0	0	0	0	1
6	1	22	0.5	0.49	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	25	7	0.06	0.00	0	6	0	1	0	0	0	0	0	0	1	0	0	2
6	1	23	0.5	0.49	0	3	2.3	3	3	1	1	1	0	0	0	2	6	15	30	30	30	19	5	0.50	0.02	0	5	-1	1	0	1	1	1	0	0	1	0	1	6
6	1	24	0.5	0.49	0	1	0.6	1	1	1	0	0	0	0	0	9	30	30	30	30	30	22	10	0.05	0.02	2	6	3	0	0	0	0	0	0	0	0	1	1	2
6	1	25	0.5	0.49	0	6	4.7	5.5	6	1	1	1	1	1	1	2	3	6	9	10	16	24	26	0.07	0.00	2	21	4	1	1	1	1	1	1	1	0	1	1	9
6	1	31	0.5	0.49	0	2	0.7	1	2	1	1	0	0	0	0	12	28	30	30	30	30	23	4	0.00	0.00	0	4	0	0	0	0	1	0	0	0	1	1	0	3
6	1	32	0.5	0.49	0	1	1.7	2	2	1	1	0	0	0	0	3	6	30	30	30	30	23	5	0.20	0.00	0	5	-1	1	0	0	1	0	0	0	1	0	1	4
6	1	33	0.5	0.49	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	21	1	0.00	0.00	1	1	-1	0	0	0	1	1	0	0	0	0	0	2

6	1	34	0.5	0.49	0	1	0.7	1	1	1	0	0	0	0	0	10	30	30	30	30	30	20	6	0.00	0.00	0	5	0	1	0	0	0	0	0	0	1	1	0	3
6	1	35	0.5	0.49	0	3	1.3	1	3	1	1	1	0	0	0	10	16	26	30	30	30	25	15	0.00	0.00	1	13	1	1	1	1	1	0	0	1	1	0	1	7
6	2	6	0.5	0.49	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	20	10	0.00	0.00	0	7	1	0	0	0	0	0	0	0	0	0	0	0
6	2	7	0.5	0.49	100	3	1.8	2	3	1	1	1	0	0	0	6	12	20	30	30	30	21	3	0.19	0.00	2	2	0	1	0	1	1	1	0	1	0	1	1	7
6	2	8	0.5	0.49	100	6	5.2	6	6	1	1	1	1	1	1	2	4	5	6	7	7	26	18	0.00	0.00	1	10	7	0	1	0	1	0	1	0	1	1	0	5
6	2	9	0.5	0.49	100	1	0.3	0	1	1	0	0	0	0	0	14	30	30	30	30	30	22	16	0.18	0.00	1	12	3	1	0	0	0	0	0	0	1	0	0	2
6	2	10	0.5	0.49	100	3	2.0	2.5	3	1	1	1	0	0	0	6	10	16	30	30	30	23	18	0.26	0.00	6	9	8	1	0	1	1	0	0	1	0	1	1	6
6	2	16	0.5	0.49	100	2	2.1	2	3	1	1	1	0	0	0	5	7	17	30	30	30	21	1	0.00	0.00	0	1	-1	1	1	1	1	0	0	0	1	0	1	6
6	2	17	0.5	0.49	100	1	0.8	1	2	1	1	0	0	0	0	12	20	30	30	30	30	25	1	0.00	0.00	0	1	-2	1	1	0	0	1	0	0	0	0	0	3
6	2	18	0.5	0.49	100	1	0.8	1	1	1	0	0	0	0	0	8	30	30	30	30	30	22	21	0.44	0.02	2	17	3	0	0	0	0	1	0	0	0	0	0	1
6	2	19	0.5	0.49	100	0	0.1	0	1	1	0	0	0	0	0	1	30	30	30	30	30	22	1	0.00	0.02	0	-1	1	1	0	1	0	0	0	0	1	0	1	4
6	2	20	0.5	0.49	100	1	0.3	0	1	1	0	0	0	0	0	10	30	30	30	30	30	20	26	0.68	0.00	3	18	8	1	0	0	1	0	0	0	0	0	1	3
6	2	26	0.5	0.49	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	4	0.04	0.00	1	2	1	0	0	0	0	0	0	0	0	0	0	0
6	2	27	0.5	0.49	100	1	0.9	1	2	1	1	0	0	0	0	4	6	30	30	30	30	23	4	0.00	0.00	0	0	2	0	0	0	0	0	0	0	1	0	0	1
6	2	28	0.5	0.49	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	19	1	0.00	0.00	1	0	0	1	0	0	0	0	0	0	0	0	1	2
6	2	29	0.5	0.49	100	6	4.6	5	6	1	1	1	1	1	1	1	1	4	8	13	21	20	15	0.22	0.00	2	12	3	1	1	1	1	0	0	0	1	1	1	7
6	2	30	0.5	0.49	100	6	5.4	6	6	1	1	1	1	1	1	1	1	2	5	6	8	24	3	0.00	0.00	0	3	0	0	0	1	0	0	0	0	1	1	0	3
6	2	36	0.5	0.49	100	2	0.6	1	2	1	1	0	0	0	0	13	30	30	30	30	30	18	18	0.08	0.00	1	11	7	0	0	0	1	0	1	0	0	0	1	3
6	2	37	0.5	0.49	100	6	4.4	6	6	1	1	1	1	1	1	1	5	9	12	12	14	23	6	0.00	0.00	0	4	1	0	1	1	1	1	0	1	0	0	1	6
6	2	38	0.5	0.49	100	1	0.6	1	1	1	0	0	0	0	0	1	30	30	30	30	30	23	-1	0.00	0.00	0	-1	-1	1	0	0	1	0	0	0	0	1	1	4
6	2	39	0.5	0.49	100	6	5.6	6	6	1	1	1	1	1	1	1	1	1	1	5	7	22	0	0.00	0.00	0	0	0	0	1	1	1	0	0	0	1	1	1	6
6	2	40	0.5	0.49	100	1	2.1	2	3	1	1	1	0	0	0	1	3	10	30	30	30	20	2	0.21	0.00	0	0	2	1	0	0	1	0	1	1	1	1	1	7
6	3	41	0.8	0.28	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	19	2	0.05	0.00	0	2	-2	1	0	0	0	0	1	0	0	0	0	2
6	3	43	0.8	0.28	0	5	3.5	4	5	1	1	1	1	1	0	2	4	9	13	22	30	22	12	0.15	0.00	0	11	2	1	1	1	1	0	1	0	1	1	0	7
6	3	45	0.8	0.28	0	2	1.4	2	2	1	1	0	0	0	0	5	14	30	30	30	30	20	12	0.00	0.00	1	8	3	1	0	0	0	1	0	0	1	0	1	4
6	3	47	0.8	0.28	0	2	1.4	1.5	2	1	1	0	0	0	0	4	16	30	30	30	30	19	4	0.00	0.00	0	4	-2	1	0	0	1	1	0	0	1	0	1	5
6	3	49	0.8	0.28	0	1	0.2	0	1	1	0	0	0	0	0	20	30	30	30	30	30	22	0	0.00	0.00	1	-2	0	0	0	0	0	1	0	0	0	0	1	2
6	3	51	0.8	0.28	0	2	1.6	2	2	1	1	0	0	0	0	4	9	30	30	30	30	20	13	0.25	0.00	0	9	2	1	1	0	0	0	1	0	1	0	1	5
6	3	53	0.8	0.28	0	1	0.9	1	1	1	0	0	0	0	0	4	30	30	30	30	30	26	0	0.00	0.00	0	-1	0	0	1	0	0	1	0	0	0	0	0	2
6	3	55	0.8	0.28	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	26	6	0.00	0.00	1	0	6	0	0	0	1	0	0	0	0	0	1	2
6	3	57	0.8	0.28	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	-2	0.00	0.00	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0
6	3	59	0.8	0.28	0	1	0.9	1	2	1	1	0	0	0	0	5	16	30	30	30	30	25	4	0.00	0.00	0	3	0	0	0	0	0	0	0	0	0	0	1	1
6	3	61	0.8	0.28	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	26	-1	0.00	0.00	0	-2	-1	1	0	0	0	0	0	0	0	0	1	2

6	3	63	0.8	0.28	0	2	1.3	2	2	1	1	0	0	0	0	7	15	30	30	30	30	23	7	0.11	0.00	3	6	0	0	0	0	1	0	1	0	1	0	0	3
6	3	65	0.8	0.28	0	3	1.4	2	3	1	1	1	0	0	0	5	9	26	30	30	30	23	25	0.33	0.00	0	19	6	0	0	1	1	0	1	1	1	0	1	6
6	3	67	0.8	0.28	0	2	1.1	1	2	1	1	0	0	0	0	7	20	30	30	30	30	21	6	0.00	0.00	1	4	0	1	0	0	1	0	1	0	0	0	1	4
6	3	69	0.8	0.28	0	1	0.6	1	1	1	0	0	0	0	0	12	30	30	30	30	30	23	12	0.08	0.00	1	6	5	1	0	0	0	1	0	0	0	0	1	3
6	3	71	0.8	0.28	0	2	1.0	1	2	1	1	0	0	0	0	6	11	30	30	30	30	24	13	0.07	0.00	2	6	6	0	0	0	1	1	1	0	1	0	0	4
6	3	73	0.8	0.28	0	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	24	17	0.00	0.00	0	11	5	0	0	0	0	0	0	0	0	0	0	0
6	3	75	0.8	0.28	0	1	0.2	0	1	1	0	0	0	0	0	24	30	30	30	30	30	22	8	0.00	0.00	0	6	1	1	0	0	0	0	0	0	1	0	1	3
6	3	77	0.8	0.28	0	2	1.1	1	2	1	1	0	0	0	0	7	23	30	30	30	30	22	1	0.00	0.00	0	1	-1	1	1	0	1	0	0	0	0	1	0	4
6	3	79	0.8	0.28	0	1	0.1	0	1	1	0	0	0	0	0	28	30	30	30	30	30	25	34	0.24	0.00	2	28	7	1	0	0	1	0	1	0	1	0	1	5
6	4	42	0.8	0.28	100	6	2.2	1	6	1	1	1	1	1	1	10	13	19	23	24	26	22	33	0.00	0.00	0	21	12	1	1	1	1	0	0	1	1	0	1	7
6	4	44	0.8	0.28	100	1	0.7	1	2	1	1	0	0	0	0	7	24	30	30	30	30	21	5	0.00	0.00	2	4	-1	1	0	0	0	1	0	1	0	0	1	4
6	4	46	0.8	0.28	100	2	1.6	2	2	1	1	0	0	0	0	1	5	30	30	30	30	20	8	0.08	0.00	0	5	1	1	0	0	0	0	0	1	1	1	1	5
6	4	48	0.8	0.28	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	-2	0.00	0.00	0	-2	-2	1	0	0	0	0	0	0	1	0	0	2
6	4	50	0.8	0.28	100	2	1.9	2	3	1	1	1	0	0	0	1	2	11	30	30	30	26	21	0.07	0.00	1	16	5	0	1	1	1	0	0	1	0	0	0	4
6	4	52	0.8	0.28	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	22	15	0.15	0.00	2	3	11	0	0	0	0	0	0	0	0	0	0	0
6	4	54	0.8	0.28	100	0	0.0	0	0	0	0	0	0	0	0	30	30	30	30	30	30	24	-2	0.00	0.00	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0
6	4	56	0.8	0.28	100	0	0.2	0	1	1	0	0	0	0	0	5	30	30	30	30	30	18	2	0.05	0.00	1	2	-1	1	0	0	1	1	0	1	0	0	1	5
6	4	58	0.8	0.28	100	5	4.2	5	5	1	1	1	1	1	0	3	4	4	6	8	30	26	19	0.50	0.00	0	15	4	1	1	1	0	1	1	1	1	1	1	9
6	4	60	0.8	0.28	100	4	1.8	2	4	1	1	1	1	0	0	6	7	20	27	30	30	24	92	0.44	0.00	5	40	51	1	1	1	1	0	1	1	1	1	0	8
6	4	62	0.8	0.28	100	1	0.5	0	1	1	0	0	0	0	0	13	30	30	30	30	30	22	4	0.00	0.00	0	3	0	1	0	0	0	0	0	0	1	0	1	3
6	4	64	0.8	0.28	100	2	0.7	1	2	1	1	0	0	0	0	4	29	30	30	30	30	22	27	0.17	0.00	2	17	10	0	0	0	1	0	0	0	0	1	0	2
6	4	66	0.8	0.28	100	2	1.7	2	2	1	1	0	0	0	0	3	7	30	30	30	30	22	27	0.23	0.00	1	19	8	0	0	0	1	1	0	0	1	1	0	4
6	4	68	0.8	0.28	100	2	2.0	2	3	1	1	1	0	0	0	1	4	27	30	30	30	20	37	0.00	0.00	1	26	10	1	1	1	1	0	0	1	1	1	1	8
6	4	70	0.8	0.28	100	2	1.0	1	2	1	1	0	0	0	0	15	18	30	30	30	30	21	3	0.05	0.00	1	1	2	1	0	0	1	0	0	0	1	0	1	4
6	4	72	0.8	0.28	100	1	1.1	1	2	1	1	0	0	0	0	1	12	30	30	30	30	21	12	0.64	0.00	1	11	1	1	0	0	0	1	0	0	1	1	0	4
6	4	74	0.8	0.28	100	1	0.8	1	1	1	0	0	0	0	0	7	30	30	30	30	30	21	11	0.00	0.00	1	7	3	1	1	0	0	0	0	0	1	1	1	5
6	4	76	0.8	0.28	100	3	2.3	2	3	1	1	1	0	0	0	1	5	17	30	30	30	26	9	0.04	0.00	0	6	2	1	1	1	0	0	0	0	1	0	1	5
6	4	78	0.8	0.28	100	1	0.3	0	1	1	0	0	0	0	0	5	30	30	30	30	30	26	35	0.00	0.00	1	20	14	1	0	0	0	1	1	0	1	0	0	4
6	4	80	0.8	0.28	100	2	0.8	1	2	1	1	0	0	0	0	4	25	30	30	30	30	20	7	0.00	0.00	0	5	0	1	0	0	1	1	0	0	0	1	1	5

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