UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Institute of Sound and Vibration Research

The influence of the magnitude of vibration on the prediction of vibration discomfort

by

James Joseph Arnold

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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The discomfort caused by the whole-body vibration of seated persons depends on the magnitude, frequency, direction, and duration of the vibration. Many legacy studies have investigated how the four main attributes of whole-body vibration influence discomfort and these have led to standardised methods for evaluating vibration to predict discomfort. The aim of the research in this thesis was to investigate the application of the methods when predicting discomfort caused by multi-axis and multiple-frequency vibration.

The first experiment investigated discomfort caused by pitch oscillation of a rigid seat with and without a backrest. Seated participants used magnitude estimation to indicate their discomfort during sinusoidal vibration at frequencies from 0.5 to 5 Hz. At frequencies greater than 1.0 Hz, the discomfort and the rate-of-growth of discomfort was greater with the backrest. At frequencies less than 1.0 Hz, the discomfort and the rate-of-growth of was similar in both seating conditions.

The second experiment investigated discomfort caused by six-axis vibration recorded in a road vehicle. Participants used the method of paired comparisons to judge differences in discomfort between six vibration conditions obtained by modifying the recorded vibration. Two scenarios involved reductions of either 50% or 100% in the vibration magnitude in each of five axes (fore-and-aft, lateral, vertical, roll, or pitch) and a control motion. No statistically significant differences in discomfort were found when reducing the vibration magnitude in any single axis prompting further investigation into the method of combining motions when predicting vibration discomfort.

The third experiment investigated how vibration discomfort depends on the frequency and magnitude of translational vibration. Seated participants judged the discomfort produced by sinusoidal vibration from 1.0 to 10 Hz using magnitude estimation. It was found that the rate-of-growth of discomfort varied between directions and frequencies of vibration, resulting in different equivalent discomfort contours at different magnitudes. Horizontal vibration at magnitudes lower than those used when developing the current standards were judged more uncomfortable than vertical vibration at frequencies greater than the 3.15 Hz equivalence frequency.

The final experiment investigated the prediction of vibration discomfort caused by combinations of different directions and different frequencies of vibration. Using magnitude estimation, seated participants judged the discomfort of single-axis, dual-axis, and tri-axial translational motions (one-octave bandwidth random motions centred on 2.0, 4.0, or 8.0 Hz). In addition, participants judged the discomfort caused by multiple-frequency single-axis motions in each of the three axes. It was found that when using ‘power summation’ of subjective measures of components in a complex motion, the power required to predict the discomfort depends on the rate-of-growth of discomfort.

The findings from the four experiments show that the rate-of-growth of discomfort is crucial when attempting to predict discomfort caused by individual vibration components, multiple-frequency vibration, and multi-axis vibration. The rate-of-growth of discomfort is highly dependent on the frequency and direction of vibration, so the inter-axis equivalence between vibration in different directions changes when the magnitude changes. Single frequency weightings and axis multiplying factors cannot provide good predictions of vibration discomfort over a wide range of vibration magnitudes. Different frequency weightings and different axis multiplying factors are required for different magnitudes of vibration.

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Academic Thesis: Declaration of Authorship

I, JAMES JOSEPH ARNOLD……..

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

The influence of the magnitude of vibration on the prediction of vibration discomfort....................

....

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

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Signed: ....

Date: ....

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Definitions and Abbreviations

ψ	Subjective magnitude (discomfort)
φ	Objective magnitude (in general, r.m.s. acceleration)
θ	Angle of rotation
k	‘Constant’ in Stevens power law
n	‘Exponent’ in Stevens power law
α	Power used to sum subjective magnitude estimates in a power summation equation
β	Power used to sum objective magnitudes in a power summation equation
f	Frequency
F	F-statistic defined as the quotient of the variance of the variable being tested and the variance of the error.
p	Number of participants for Scheffe’s method of paired comparisons
r.m.s.	Root-mean-square: r.m.s. = $\left[\frac{1}{T}\int_0^T a(t)^2 dt\right]^{1/2}$
r.m.q.	Root-mean-quad: r.m.q. = $\left[\frac{1}{T}\int_0^T a(t)^4 dt\right]^{1/4}$
VDV	Vibration dose value: VDV = $\left[\int_0^T a(t)^4 dt\right]^{1/4}$
r.s.s.	Root-sums-of-squares: r.s.s. = $a = \left(a_{xw}^2 + a_{yw}^2 + a_{zw}^2\right)^{1/2}$
r.s.q.	Root-sums-of-quads: r.s.s. = $a = \left(a_{xw}^4 + a_{yw}^4 + a_{zw}^4\right)^{1/4}$
SEAT	Seat Effective Amplitude Transmissibility: SEAT = $\mathrm{SEAT\%} = \left[\frac{\mathrm{VDV\ on\ the\ seat}}{\mathrm{VDV\ on\ the\ floor}}\right] \times 100$
MTVV	Maximum Transient Vibration Value: MTVV = max$\left\{\left[\frac{1}{T}\int_{t_0}^{t_0+\tau} a_w(t)^2 dt\right]^{1/2}\right\}_{t_0=0..T-\tau}$

Chapter 1 Introduction

Drivers and passengers of vehicles experience vibration originating from the road (potholes, speed bumps, rough tarmac, etc.) as well as from the moving parts within a vehicle (engine, gearbox, driveshaft, etc.). Vehicle refinement has become an important part of the automotive industry as vehicle ride becomes a differentiator in perceived quality of different brands.

Computer Aided Engineering (CAE) models of vehicles and components are created and the vibrations expected to reach the passengers are calculated and then analysed using models for predicting human vibration discomfort as in British Standard 6841 (1987) and International Standard ISO 2631-1 (1997). Bespoke prototypes are then created and the vibration experienced by drivers and passengers, referred to as 'ride comfort', is evaluated subjectively by test drivers and objectively using measurements of acceleration, commonly in the three translational directions on the floor or seat rail, despite recommendations from the above standards to measure the three translational directions on the floor, seat pan and backrest and the three rotational directions on the seat pan. An increase in the power to predict vibration discomfort would lead to fewer prototypes necessary before a final acceptable level of ride comfort is achieved.

The British and International standards advocate a single frequency weighting and single axis multiplying-factor for predicting the vibration discomfort caused by each direction of acceleration at each location of vibration entering the body (the seat, back, and feet). By having only a single frequency weighting for each component of vibration, the standards assume that the frequency-dependence of vibration discomfort does not depend on the magnitude of the vibration. Research conducted subsequent to the publication of the standards has shown that the human response to vibration can be estimated using Stevens' power law (Stevens, 1975) and that the rate-of-growth of discomfort is dependent on the frequency, the direction, and the location of the vibration experienced (Morioka and Griffin 2006a, b, 2010a; Wylie and griffin 2007, 2009; Thuong and Griffin 2011; Basri and Griffin, 2013, Beard and Griffin 2012, 2013, 2014, 2016). This results in sensitivity to each frequency, direction, and location depending on the magnitude of the vibration. It can therefore be assumed that the relative sensitivity between axes at different frequencies differs when the magnitude of the vibration changes, however it is currently unclear how the relative sensitivity differs.

The standards do not advocate the use of translational acceleration data from the floor of a vehicle to predict vibration discomfort of a seated person, although this remains common practice in parts of the automotive industry. A main contribution to vibration discomfort in a passenger vehicle can be fore-and-aft vibration at the backrest (Parsons *et al*., 1982). One cause of fore-and-aft vibration at the backrest is pitch oscillation of the vehicle, which may not cause much fore-and-aft acceleration at the floor of a vehicle, depending on the centre-of-rotation of the pitch oscillation (Qui and Griffin, 2005). The effect of a backrest on the rate-of-growth of discomfort of seated persons during pitch oscillation at frequencies greater than 1.6 Hz, investigated by Wyllie and Griffin (2009), is currently unknown. A typical range of interest for this type of motion may be up to 5.0 Hz, so increased understanding of the effect of the backrest on the rate-of-growth of discomfort up to 5.0 Hz would be beneficial when seeking to reduce vibration discomfort in vehicles.

Investigations of human response to dual-axis and tri-axial whole-body vibration have used either sinusoidal motion at differing frequencies or random motion centred on the same frequency (Whitham 1977; Fairley and Griffin 1988; Mistrot *et al.,* 1990). The standards currently allow an overall ride value to be calculated comprising of the root-sums-of-squares (r.s.s.) of the frequency-weighted vibration from 12 inputs (6 axes at the seat, 3 axes at the back, and 3 axes at the feet) and suggest reporting the component ride values for each input. It has not been demonstrated experimentally that the advised r.s.s. method is applicable to random motion centred on different centre frequencies or different directions. It is an open question whether the dependence of the rate-of-growth of discomfort on the frequency, direction, and location of vibration has a large effects on the vibration discomfort caused by multi-axis vibration.

The main objectives of the research can be described by three questions: (I) how does a backrest affect the rate-of-growth of vibration discomfort and equivalent comfort contours for pitch oscillation of seated persons in the frequency range 0.5 to 5 Hz? (II) How does the magnitude-dependence of the frequency-dependence of vibration discomfort affect the inter-axis equivalence of discomfort for the vibration of seated persons in the fore-and-aft, lateral, and vertical axes over the frequency range of 1.0 to 10 Hz? (III) When using a power summation method to predict discomfort caused by octave-bandwidths of random multi-axis vibration, what power is appropriate, and does the rate of growth of discomfort affect the optimum value used in the power summation?

This thesis is structured into nine Chapters:

Chapter 1 introduces the research questions that are to be answered by the thesis.

Chapter 2 reviews the available literature investigating vibration discomfort, including the research that lead to the current standards. A portion is also focused on psychophysics, describing the origins and uses of magnitude estimation and other psychophysical techniques. This chapter culminates with three questions that are unanswered about the human response to vibration in the seating conditions, magnitude range, and frequency range commonly experienced in cars.

Chapter 3 describes the research methodology, statistical techniques and equipment used in the experimental work of this thesis.

Chapter 4 is the first experimental chapter. It investigates the discomfort caused by whole-body pitch oscillation and compares the rate-of-growth of discomfort and equivalent comfort contours of pitch oscillation with and without a backrest present.

Chapter 5 is the second experimental chapter. It investigates the change of discomfort experienced from a 6-axis motion when each of five (fore-and-aft, lateral, vertical, roll, or pitch) axes of motion is reduced.

Chapter 6 is the third experimental chapter. It investigates the discomfort caused by sinusoidal fore-and-aft, lateral and vertical motion in the frequency range of 1.0 to 10 Hz. The rate-of-growth of discomfort caused by each axis and each frequency of vibration is compared as well as the equivalent discomfort between frequencies and axes at different magnitudes.

Chapter 7 is the fourth experimental chapter. It investigates the discomfort caused by octave-band random multi-frequency single axis vibration, dual-axis vibration and tri-axial vibration. The prediction of discomfort with the use of a power summation method of the individual components of the vibration is also investigated.

Chapter 8 discusses the results obtained in the experimental work of this thesis, how it fits with current prediction methods, and where improvements may be made to current methods using the results from the experimental work.

Chapter 9 presents the main conclusions of this thesis and proposes future work that could increase understanding based on the findings on this study.

These nine Chapters answer the objectives stated above with the following original contributions: (I) The rate-of-growth of discomfort during pitch oscillation was found to be similar with and without a backrest at frequencies up to about 1 Hz, above 1 Hz the rate-of-growth of discomfort decreased with increasing frequency in the condition without the backrest and remained reasonably constant with the backrest. The consequence of this is that discomfort at frequencies of about 1 Hz and below was similar with and without a backrest at all magnitudes, whereas at frequencies above 1 Hz the additional discomfort caused by the backrest was small at low magnitudes and the difference between conditions increased with increasing magnitude. (II) The rate-of-growth of discomfort was found to depend on both the frequency and the direction of translational motion, especially in the fore-and-aft and lateral axes where after peaks at 2.5 Hz and 1.6 Hz respectively, the rate-of-growth of discomfort decreases with increasing frequency. The percentage difference in the median rate-of-growth of discomfort in the vertical direction was lower than both horizontal directions and did not have the same systematic decrease with increasing frequency. The result of this is that at low magnitude, people are more sensitive to horizontal vibration than current standards predict in relation to vertical vibration. The frequency at which greatest sensitivity changes from horizontal vibration to vertical vibration decreases with increasing magnitude. (III) No single power using in a power summation method could predict the discomfort caused by dual-axis and tri-axial random vibration without significant errors with some combinations of stimuli. Predictions of tri-axial discomfort has highly correlated with average rates-of-growth of discomfort suggesting that the power summation may depend on the rate-of-growth of discomfort of each component of vibration.

Chapter 2 Literature review

2.1 Introduction

This chapter discusses current understanding of vibration discomfort and the process of measurement, evaluation, and assessment of objective values to predict the discomfort of seated people.

The review starts by describing psychophysics as a concept and ways in which it might be used to measure vibration discomfort. Following on from this basic understanding, some concepts will be introduced such as the equivalent comfort contour, a descriptor of the frequency-dependence of vibration discomfort, and how this might be determined using various psychophysical methods (Section 2.2).

Section 2.3 moves the focus to what influences vibration discomfort. In this section, what influences vibration discomfort, including vibration magnitude, vibration direction, vibration duration and vibration frequency, are considered and how these might be measured and accounted for. Following this, the development of frequency weightings is reviewed, including the underlying principles and the weightings evolved. This leads on to the development of the current British Standard 6841 in 1987 and the current International Standard 2631-1 in 1997 which include multiplying factors for different axes of vibration as well as different input locations and summation methods for combining values.

The current knowledge of complex motions involving non-sinusoidal, multiple-frequency and multiple-axis is reviewed in Section 2.5. Comparisons are drawn from the relationship between studies carried out using simple or complex motions providing clarification of the suitability of conclusions drawn from simple tests on complex real-world motion. Static comfort (Section 2.4) is also mentioned as this may impact discomfort both in laboratory testing and real-world discomfort, noting that increasing static comfort may affect dynamic comfort. Seating dynamics and the SEAT value are described and related to how they affect vibration discomfort.

Vibration discomfort tools and methods from the International Standard 2631:1974 to the current British and International standards are reviewed (Section 2.6) with respect to the measurement, evaluation and assessment of vibration discomfort. Included is a detailed insight into the origins of these methods and how the research has been implemented in the standards. Remaining challenges to the current methods are identified (Section 2.7) and gaps in the current knowledge are detailed and questions to develop evaluation techniques for vibration discomfort are proposed.

2.2 Psychophysics

2.2.1 Introduction

Psychophysics, established by Gustav Theodor Fechner in 1860, is the study of the relationship between physical and psychological events, in other words, the relationship between a stimulus and a sensation. More recently, in the mid-to-late 20th century, Stevens described the relationship between physical stimuli and psychological magnitude as a power law relationship now known as the Stevens' Power Law, successfully demonstrating that a power law governs the human response of both light and sound by 1953 (Stevens, 1975). Vibration discomfort is the subjective sensation caused by objective vibration stimuli.

2.2.2 Psychophysics

2.2.2.1 Subjective and objective

In the psychophysical domain, the key interest is in the subjective response (referred to as ψ) of an objective stimulus (referred to as φ). A distinguishing factor between subjective and objective measurement can be seen in the vocabulary. A weighing scale can measure the weight of something, a human can measure its heaviness, a sound level meter can measure the sound pressure level and frequency content of an acoustic signal, a human can measure its loudness and its pitch (among other attributes).

Problems may arise with the study of psychophysics; '*if something is considered as wholly subjective it often carries the weight of something suspect or untrustworthy*' (Stevens, 1975). However this can readily be dismissed by performing a simple experiment such as asking participants to decide which of two different weights is heavier or which of two different sounds is louder etc. (Stevens, 1975). Once this simple experiment shows that humans can measure the sensation of heaviness from weight or the sensation of loudness from sound pressure, the problem changes from 'Can we measure sensation?' to 'How do we measure sensation?'

2.2.2.2 Measurement from human

'*Humans can elicit both verbal and non-verbal responses to stimuli*' (Stevens, 1975), even without being asked (e.g., saying that a sound is quiet, shielding their eyes from a bright light etc.). '*However, in an experimental situation, some responses to stimuli can be more useful than others.*

If a participant is lifting a weight, instead of asking an open-ended question about its heaviness it can be helpful to both the participant and the experimenter to suggest that the participant assigns a number that represents the heaviness of the weight' (Stevens, 1975). Knowledge of the type of scale to use is crucial to aid the participant on how to determine the number assigned to a stimulus.

2.2.2.3 **Psychophysical scales**

There are four types of number scales, each with their own properties and uses. The choice of scale in psychophysical experimentation can limit the use of the measurement obtained from a subject. Table 2.1 provides some detail about the four types of scale.

One key difference between an interval scale and a ratio scale is that a ratio scale has a true zero whereas an interval scale has an arbitrary one. An example of this is that it is possible to have zero length and this can be represented by zero meters, but in temperature Celsius zero degrees is not equivalent to zero temperature. Another way to view this is that two meters is twice as long as one meter but 20 degrees Celsius does not have twice as much energy as 10 degrees Celsius.

2.2.3 Psychophysical laws

2.2.3.1 **Weber-Fechner's Law**

'*E. H. Weber when working mainly with the discrimination of lifted weights discovered that two relatively heavy weights must differ by a greater amount than two relatively light weights for one weight to be perceived as heavier than the other*' (Gescheider, 1985). He decided that the size of the difference threshold between two stimuli was a linear function of stimulus intensity, and thus, increases in the intensity of the stimulus that were noticeably different to the observer were always a constant fraction of the stimulus intensity, this is now known as the Weber's fraction. This forms part of what is now known as Weber's law and can be written as:

$$\Delta\phi = c\phi \tag{2.1}$$

where $\Delta\Phi$ is the smallest change in stimulus that can be discriminated (also known as a just noticeable difference, or, jnd), c is a constant fraction (the Weber's fraction), and, Φ is the starting intensity of the stimulus.

Table 2.1 Scales of measurement from Table 2 in Stevens (1975).

Scale	Operations we perform	Permissible transformations	Some appropriate statistics	Examples
Nominal	Identify and classify	Substitution of any number for any other number	Number of cases Mode Contingency correlation	Numbering football players Model numbers
Ordinal	Rank order	Any change that preserves order	Median Percentiles Rank-order correlation	Preference lists Hardness of minerals Rank lists
Interval	Find distances or differences	Multiplication by a constant Addition of a constant	Mean Standard deviation Product-moment correlation	Temperature Fahrenheit Temperature Celsius Calendar time Standard scores
Ratio	Find ratios, fractions, or multiples	Multiplication by a constant only	Geometric mean Percent variability	Length, weight, numerosity, duration, and most physical scales Temperature Kelvin Loudness in sones

Through experimentation it was discovered that this law breaks down close to the absolute threshold of sensation where a stimulus is reliably detectable. A common deviation from Weber's law is:

$$\Delta\phi = c(\phi + a) \tag{2.2}$$

where *ca* is the absolute threshold of sensation. It is possible to see in the above expression that when Φ is large the difference threshold approaches $c\Phi$ and approximates Equation 2.1. However when Φ is small, Equation 2.2 appears to fit better with data collected by Riesz in 1928 (Gescheider, 1985).

G. T. Fechner proposed that '*an arithmetic series of mental intensities might correspond to a geometric series of physical energies'* (Gescheider, 1985). Weber's results seem to imply this idea, that a greater change in intensity is required to change the sensation magnitude as intensity increases. Fechner suggested relating the values of $\Delta\Phi$ on the physical scale to the jnd in sensation on the psychological scale with the assumption that all jnd's were equal psychological units regardless of differences in the size of $\Delta\Phi$. Fechner created a scale by counting the number of jnd's starting at the threshold of sensation where he assumed to correspond to a magnitude of zero on the psychological scale (Gescheider, 1985).

Fechner noticed that if the sensation magnitude is plotted against the logarithm of the stimulus intensity then the relationship is linear, he derived a general formula from Weber's law by integrating over values of Φ and is commonly known as Fechner's law:

$$\psi = k \log_{10} \phi \tag{2.3}$$

where ψ is sensation magnitude and Φ is stimulus intensity in units above the threshold of perception.

Fechner's law relies on the assumption that jnd's are equal increments in sensation. Experimental testing (Stevens, 1936) however has shown that jnd's are psychologically not equal and thus cannot be treated as a ratio scale (e.g., '*a sound 10 jnd's above the threshold of hearing is not half as loud as 20 jnd's above'* (Stevens, 1975)). Because of this, there is an inherent problem in measuring psychological sensations with jnd's where a ratio scale would be most useful.

2.2.3.2 Stevens' power law

As seen above, when trying to determine a psychophysical law that works as a ratio scale it is necessary to have the data presented on a ratio scale, therefore no assumptions need to be made on whether jnd's are of equal psychological intensity.

By asking participants to produce ratios of sensation (see psychophysical methods section 2.1.4) Stevens was able to determine a new psychophysical law based on the ratios of sensations given by participants. By 1953, Stevens had managed to show that a power law governed human reactions to both light and sound (Stevens, 1975) and presented his new psychophysical law named the Stevens' power law:

$$\psi = k\varphi^n \tag{2.4}$$

where ψ is the subjective magnitude, φ is the objective magnitude, *k* is a constant and gives the units of the objective magnitude and the exponent *n* is the rate-of-growth of sensation. Since 1953, over three-dozen continua have been investigated at Harvard and have all shown to be governed by Stevens' power law (Stevens, 1975).

A useful feature of the power law can be found through the logarithmic transformation of it:

$$\log_{10}\psi = n\log_{10}\varphi + \log_{10}k \tag{2.5}$$

Equation 2.5 describes a straight line when plotted on log-log coordinates, the gradient of which is equal to the exponent *n* from Equation 2.4. This allows for the simple calculation of the values of *n* and *k* by means of linear regression.

Whilst out of scope of this thesis, it is worth mentioning that at magnitudes close to the threshold limit of sensation, Stevens' power law also benefits from a threshold adjustment similar to the deviation in Weber's law (Equation 2.2). With the threshold adjustment, Stevens' power law can be written as:

$$\psi = k(\varphi - \varphi_0)^n \tag{2.6}$$

This additive constant has been shown to be useful describing sensations caused by low-magnitude whole-body vibration and hand-transmitted vibration (Morioka and Griffin 2006a,b).

Results reported by Stevens (1975) support the use of Stevens' power law for a wide array of psychological continua and compelling arguments are made for its use in the discipline of psychophysics.

2.2.4 Psychophysical methods

2.2.4.1 Relative magnitude estimation

Magnitude estimation is a method by which a subject would, for example, say a number based on how large they judge the magnitude of a stimulus.

Relative magnitude estimation uses a reference stimulus and test stimuli, sometimes presented in pairs, where the sensations provoked by the reference stimulus is given a numerical value (i.e., 100) (Stevens, 1975). The subjects state a value for the sensation caused by each test stimulus based on their perception of the subjective magnitude it appears to be expressed as a ratio of the subjective magnitude of the reference motion. For example if the subjects feel the test stimulus is twice the magnitude of the reference stimulus they would assign it a value of 200, similarly if they feel it was half the magnitude of the reference motion they would assign it a value of 50.

The method of relative magnitude estimation can be time consuming as a reference is repeated for every test stimulus, and both reference and test stimuli are repeated in some cases. Below, the method of absolute magnitude estimation reduces the experimental time by not repeating the reference stimulus.

2.2.4.2 Absolute magnitude estimation method

Similar to relative magnitude estimation, absolute magnitude estimation requires subjects to assign a numerical value to the magnitude of a stimulus. In its truest form, there is no reference value at all for subjects and from the first stimulus in a sequence the subject will assign whatever value they believe is appropriate and base further values upon that initial one.

There is a possible problem with allowing such freedom for the choice of the first stimulus which is allowing for scaling. Depending on the choice of the first stimulus and the subjects' experience, they may choose a value too low to allow for reasonable answers for some of the other stimuli. This could cause problems assigning reasonable values for low magnitude stimuli and therefore artificially lower the rate-of-growth if used for obtaining values for n and k in Stevens' Power Law (Equation 2.4).

A variation of the method to reduce this problem is for an initial reference stimulus to be given to subjects at the beginning of the experiment, around the centre of the magnitude range to be used during the experiment and suggest that they assign it a value of 100 to allow for headroom at the lower end of the ratio scale.

Despite this concern, there are experiments that show a true absolute magnitude estimation can prove useful. Stevens (1956) produced a loudness function of a 1000 Hz tone using 32 subjects and two judgements per subject using the true absolute magnitude estimation method that followed the Stevens' power law successfully.

2.2.4.3 Magnitude production

Another method to obtain magnitudes from subjects used by Stevens is essentially the reversal of the method of magnitude estimation and called magnitude production (Stevens, 1975). In this scenario, the experimenter may read out a series of numbers in an irregular order. For each number supplied, the subject has to increase or decrease the stimulus to match the number supplied by the experimenter.

Whilst using both methods for similar experiments, Stevens noticed a slight systematic difference between the method of magnitude estimation and magnitude production. Described as possibly originating from a regression to the mean (subjects limiting the range of values they use to the centre of the range), it appears that magnitude estimation may slightly underestimate the exponent *n* in the power law and the method of magnitude production may slightly overestimate the exponent. Whilst Stevens recommends, where possible, to carry out a balanced experiment using both magnitude estimation and magnitude production, he notes that this may not always be possible as there is often no way to give control of a stimulus to a subject. For this reason, he states that '*magnitude estimation has become the scaling procedure most often used. I can think of no circumstance in which it may not be applied'* (Stevens, 1975).

2.2.4.4 Paired comparisons method

The method of paired comparisons consists of stimuli presented in pairs to a subject and the subject states which one they 'prefer' (or a variation of this such as 'which vibration feels greater in magnitude'). In a paired comparisons experimental design, all of the stimuli are paired with all other stimuli, so the method is very time-consuming if there are many stimuli (e.g., if six stimuli are used in both an a-b and b-a order, 30 pairs will be presented). Statistical methods have been developed to allow the findings to be used to place the stimuli on a ratio scale.

A variation on the basic method of paired comparisons allows subjects to declare the pair of stimuli 'equal' (Odesky, 1967), otherwise the method of paired comparisons involves a 'forced choice' between two stimuli.

A multiple point scale such as a seven point scale (3, 2, 1, 0, -1, -2, -3) may be given as a preference scale to subjects where positive values give the strength of preference to stimulus 'a' and negative values give the strength of preference to stimulus 'b' (David, 1959).

2.2.5 Methods of obtaining equivalent comfort contours

In the following section (Section 2.3) it will be shown that vibration will usually be defined by four characteristics: duration, frequency, direction, and magnitude. The ‘equivalent comfort contour’ is a useful tool to describe the change of discomfort with frequency, although in this context and within much of the literature the words ‘comfort’, ‘discomfort’, and ‘sensation’ are sometimes interchanged.

Examples of equivalent comfort contours are given in Figure 2.1, the lines show the objective magnitude required for a person to experience the same level of discomfort at each frequency. Where the line shows a higher value, it means a greater magnitude is required to produce equivalent discomfort and so humans are less sensitive to vibration discomfort at that frequency. Where the line shows a lower value, it means that humans are very sensitive to vibration at that frequency. Many methods are available for determining equivalent comfort contours, the most popular are described below.

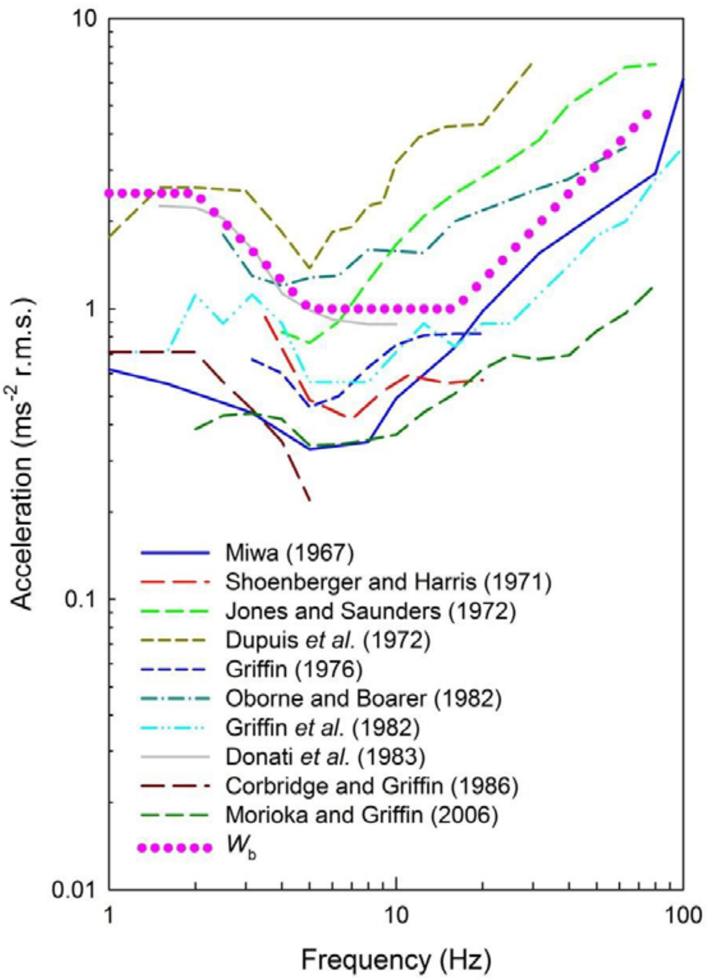

Figure 2.1 Equivalent comfort contours in the vertical direction, from Figure 2.7 Basri (2012)

2.2.5.1 Early work on equivalent comfort contours

Miwa (1967) described many previous experiments of whole-body vibration discomfort performed between 1931 and 1966 to compile a short library of the methods used. After a thorough investigation of the types of vibrators available and their suitability for the purpose of human vibration discomfort experimentation in addition to the extensive review of previous methodology, experiments were designed to produce contours of equivalent comfort for sitting and standing persons in the vertical and horizontal directions.

Described in the paper (Miwa, 1967) as the method of paired comparisons, the method used better approximates the method of constant stimuli (see Section 2.2.5.3) using a reference motion and test motions. The reference motion used was a 20 Hz sinusoidal motion at different magnitudes given as vibration acceleration level 'VAL'. Magnitudes chosen were at the threshold level and then from 20 to 50 dB in 10 dB steps for vertical vibration and threshold and from 30 dB to 60 dB for horizontal vibration. The VAL was given in dB from:

$$20\log_{10}(a/a_{ref}) \qquad (2.7)$$

where a is the r.m.s. acceleration value and a_{ref} is equal to 0.0098 ms^{-2}.

Equivalent comfort contours were produced at the five magnitudes stated above in the vertical and horizontal directions. Despite fore-and-aft and lateral motions being tested separately, only the fore-and-aft motions were presented as there was a lot of agreement between the two results. The comfort contours could be approximated by slopes of constant velocity and constant displacement with respect to frequency in both axes with the addition of constant acceleration in the vertical direction below 6 Hz.

2.2.5.2 Intensity matching method

A technique called intensity matching was used in many experiments in the 1970's (Griffin, 1976; Griffin and Whitham, 1976; Griffin and Whitham 1977), this test is a relative method where subjects would be exposed to a 'reference' stimulus and a 'test' stimulus (as a pair) and then match the test vibration to the reference vibration. This was done in a variety of ways such as giving control of the vibration magnitude to the subject (Griffin and Whitham, 1976).

One bias that can occur with this type of testing is an 'order effect' where participants are biased, to varying degrees, towards judging the second stimulus more uncomfortable, as demonstrated in Griffin and Whitham (1980a). This may not prohibit the use of intensity matching because judgements where the reference and the test are identical can be used to correct for the bias, if the bias is assumed to be similar for all stimuli.

Another bias occurs with this type of test if the subjects have control of the magnitude of the test stimulus (i.e., using the method of adjustment) because subjects tend to choose lower magnitudes than appropriate to minimise their discomfort (Griffin and Whitham 1976, 1977; Fairley and Griffin, 1988).

A third bias occurs if the reference and the test stimuli are not of equal duration (e.g., subjects take a long time to adjust the test stimulus so that they are exposed to a longer duration of the test stimulus than the reference stimulus (Griffin and Whitham, 1980b; Fairley and Griffin, 1988)).

2.2.5.3 **Method of constant stimuli**

The method of constant stimuli presents pairs of stimuli to each participant to determine equivalent comfort contours (Griffin and Whitham, 1980a). Unlike the intensity matching method, participants weren't given the option to reduce or match the pair of stimuli, instead they stated which of the two stimuli caused greater discomfort. Unlike the method of paired comparisons, instead of pairing each possible stimulus with all others, a reference was used throughout the experiment and each test stimulus was compared to the reference.

A modified version of the method of constant stimuli was employed by Griffin *et al.* (1982a) in a series of four papers that formed some of the underlying data used to shape British Standard 6841 (1987). This method was seen as a solution to a few problems that had been experienced in the traditional method of constant stimuli, where the second stimulus was consistently judged as more uncomfortable than the first stimulus. In addition, the stimuli presented to the subjects were all the same duration as this was seen to have an influence on the perception of discomfort (Griffin and Whitham, 1980b).

The method used a repeated pair ('reference'-'test'-reference'-'test') found by Griffin and Whitham (1980b) to greatly reduce the bias against the second stimulus of a single pair. The method also took the control away from the subject by presenting stimuli randomly by computer control, the computer was also able to eliminate test motions where earlier responses from subjects strongly suggested how the subjects would respond.

2.2.5.4 **Magnitude estimation**

As described in Sections 2.2.4.1 and 2.2.4.2, magnitude estimation has been used to determine equivalent comfort contours (Morioka and Griffin, 2006a; Wyllie and Griffin, 2007; Basri and Griffin, 2013; Beard and Griffin 2013a; Zhou and Griffin, 2014; Thuong and Griffin, 2015). The values of the exponent, n, and the constant, k, in Stevens' power law can be determined from linear regressions of magnitude estimations using Equation 2.5. With known values of n and k it is possible to construct equivalent comfort contours for any subjective magnitude, ψ. It is possible to see the effect of magnitude on the frequency-dependence of vibration discomfort by plotting equivalent comfort contours at many different subjective magnitudes and to look for differences in the value of the exponent *n*.

Huang and Griffin (2014) investigated and compared judgements of subjective intensity of noise and vibration using both absolute magnitude estimation and relative magnitude estimation. It was found that subjects were able to produce values for *n* and *k* used in Stevens' power law with high repeatability using both relative and absolute magnitude estimation.

The effect of the range of acceleration magnitude when using Stevens' power law was investigated by Zhou and Griffin (2014). Twenty male and twenty female subjects took part in three experiments to determine *n* and *k* values at three different ranges of acceleration magnitude. Relative magnitude estimation (see Section 2.2.4.1) was used and a 4 Hz vertical vibration reference was used in each experiment consisting of low magnitude (0.125 ms^{-2} r.m.s.), medium magnitude (0.315 ms^{-2} r.m.s.) and high magnitude (0.8 ms^{-2} r.m.s.) vibration with appropriately scaled test motions in the frequency range from 1.0 to 16 Hz.

The rate-of-growth of discomfort, *n*, and the constant, *k*, did not differ significantly between the three ranges of magnitude at any of the thirteen frequencies investigated. This suggests that the acceleration magnitude of vibration during the experiment has little or no effect on the rate-of-growth or constant in Stevens' power law and therefore equivalent comfort contours constructed by *n* and *k* values produced at one magnitude range should be suitable at higher or lower magnitude ranges as long as they are not close to threshold levels.

When the acceleration magnitude of test motions are close to threshold levels, a threshold adjustment is required (see Equation 2.6). Morioka and Griffin (2006a) saw evidence of a curvilinear relationship between sensation magnitude and vibration magnitude when plotted on log-log scales. Using the additive constant in Equation 2.6 appeared to improve the representation of sensation magnitudes at vibration magnitudes close to threshold limits.

2.3 Main factors affecting vibration discomfort

2.3.1 Introduction

When conducting scientific research it is important to understand what is being tested and to ensure that the effects of all other variables are controlled (i.e., reduced or removed) so that there is confidence that only the effects of the independent variable are observed as changes in the dependent variable. In human responses to vibration research there are many variables affecting vibration discomfort that will be discussed, however, the four main variables of a vibration are duration, frequency, direction and magnitude.

2.3.2 Duration

Knowledge of the time-dependency of vibration discomfort is necessary to understand the effects of vibration on health as well as experimental designs for investigating vibration discomfort.

The time-dependency of vertical whole-body discomfort was investigated by Griffin and Whitham (1980a, 1980b). The experiments involved matching discomfort from either 4, 8, 16 or 32 Hz test motions with that of a reference motion of 10 Hz at 1.0 ms^{-2} and a duration of 1.0 second using the method of constant stimuli. Participants pushed a button to decide whether the reference or the test motion caused greater discomfort and the results were stored in a computer.

In the first two experiments from Griffin and Whitham (1980a), logarithmic regressions over time at the four frequencies chosen produced slopes of equivalent discomfort over durations from 1 cycle to 4 seconds that ranged from -0.29 to -0.45, significantly lower than -0.5 implied by r.m.s. averaging, one of the methods implied in the ISO standard at the time (ISO 2631, 1974), see Figure 2.2 for an example. This demonstrated that r.m.s. time averaging significantly underestimated the acceleration necessary over long periods of time to cause similar discomfort of vibration over shorter durations. This lead to a suggestion by the authors to use a fourth power dependency named the root-mean-quad (r.m.q.) Figure 2.3 shows a comparison between the r.m.s., r.m.q. and the time-dependency given in ISO 2631 (1974).

In both the current British Standard (BS 6841, 1987) and in International Standard (ISO 2631-1, 1997) both r.m.s. and r.m.q methods are acceptable. Suggestions are given that motions with high crest factors (the ratio between the greatest peak of a time history and the r.m.s. of the time history) above 6 use the r.m.q. method which is more sensitive to occasional peaks (discussed in Section 2.6.3).

2.3.3 Frequency

As this thesis is concerned with the vibration of seated persons, most of the following will concentrate on the dependence on frequency of whole-body vibration discomfort in seated persons. However, some early work with standing persons is included where this posture was chosen because the vibrators were not safe for seated subjects.

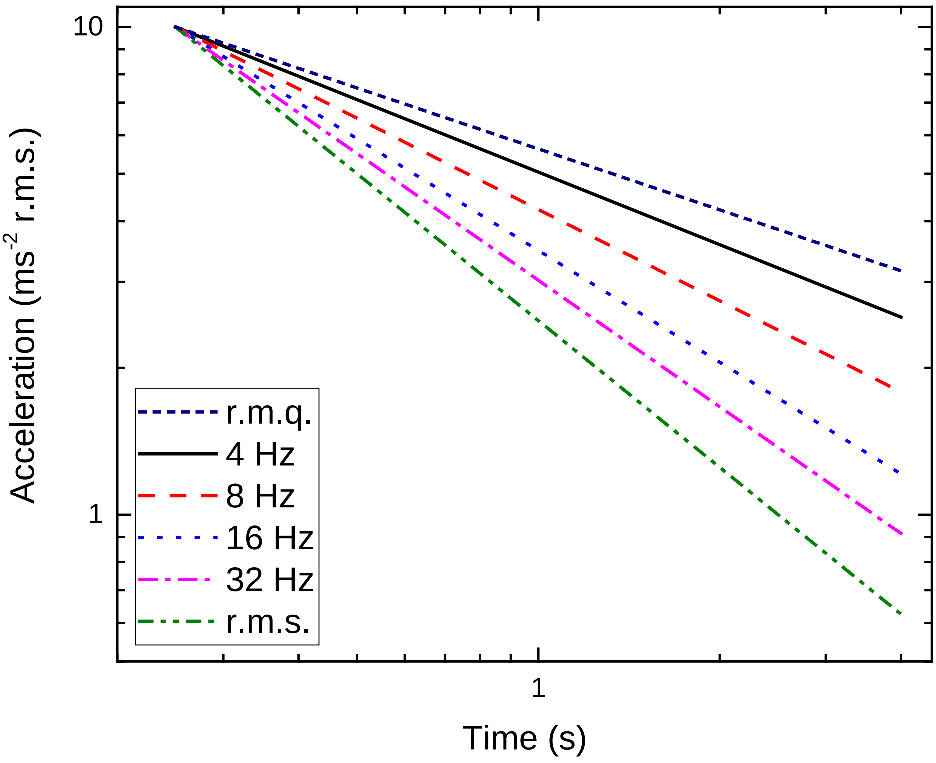

Figure 2.2 Example slopes of equivalent discomfort based on findings by Griffin and Whitham (1980a) normalised to 10 at 0.25 s compared with r.m.s. and r.m.q. averaging.

The frequency-dependence of seated persons was investigated by Miwa (1967). Using a method of constant stimuli, equivalent comfort contours were obtained using a reference motion of 20 Hz for seated persons in the vertical and horizontal directions at several magnitudes including thresholds of perception (Figure 2.4). Contours were then adjusted to give physical meaning as slopes of constant jerk, acceleration, velocity or displacement: slopes of -6 dB/octave, flat. +6 dB/octave and +12 dB/octave respectively.

It can be seen clearly from Figure 2.4 that the sensation of vibration is highly dependent on the frequency of vibration and this has influenced a large proportion of studies of human response to vibration to investigate the effect of frequency on vibration discomfort.

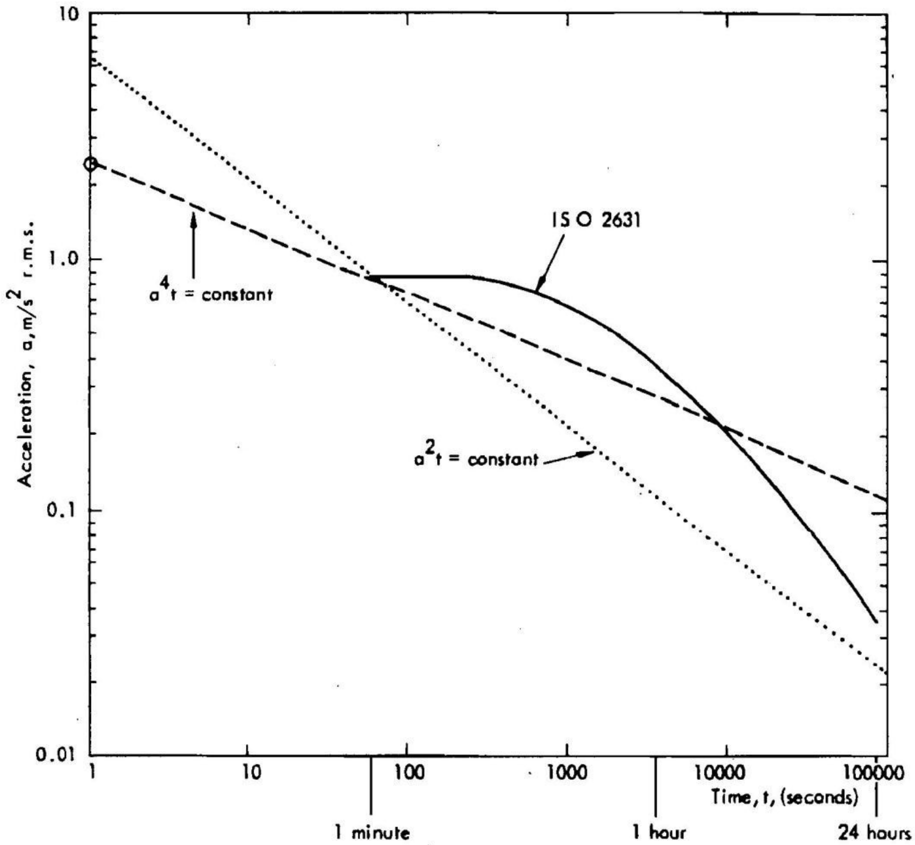

Figure 2.3 Comparison between the square relationship time-dependency implied by r.m.s., a fourth power dependency, r.m.q., and the time-dependency given in ISO 2631-1:1974 from Figure 1 in Griffin and Whitham (1980b).

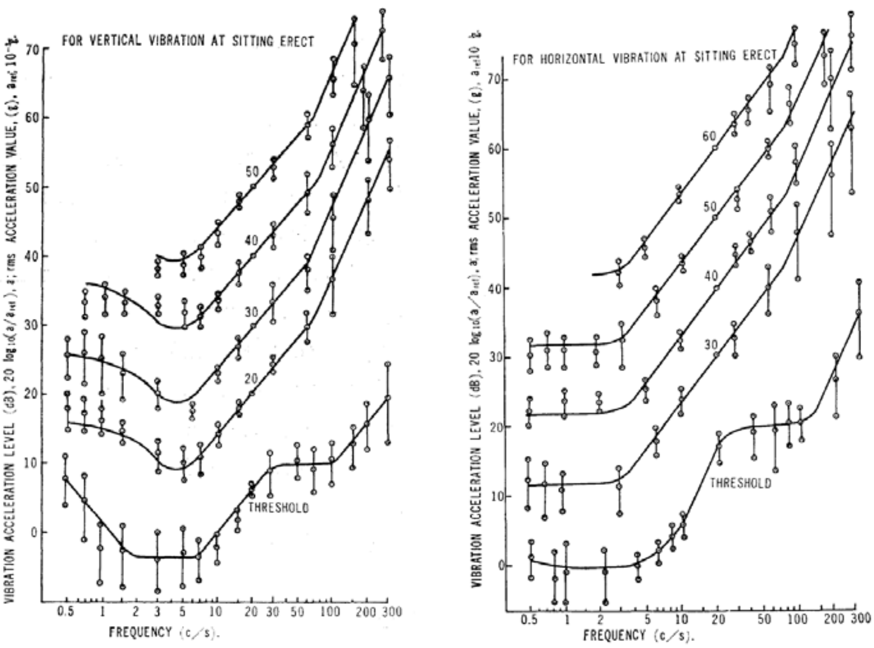

Figure 2.4 Equivalent comfort contours for vertical and horizontal vibration of seated subjects using the method of constant stimuli, from Figures 9 and 10 in Miwa (1967). The decibel scale is with reference to 10^{-3} g or 0.00981 ms^{-2}.

2.3.4 Direction

Frequency-dependence of vibration discomfort and the direction of the vibration are closely linked. As can be seen from Figure 2.4, the shapes of the equivalent comfort contours are quite different between vertical vibration and horizontal vibration. Therefore when characterising the differences between directions of vibration discomfort, it is necessary and helpful to talk about the frequency-dependence in each direction.

2.3.4.1 Vertical seat vibration

The focus of many investigations of vibration discomfort has been concerned with vertical vibration. Across many different studies (Miwa, 1967; Shoenberger and Harris, 1971; Griffin 1976; Griffin *et al.,* 1982a; Corbridge and Griffin, 1986; Morioka and Griffin, 2006a) there are similarities between the equivalent comfort contours obtained by the various methods used.

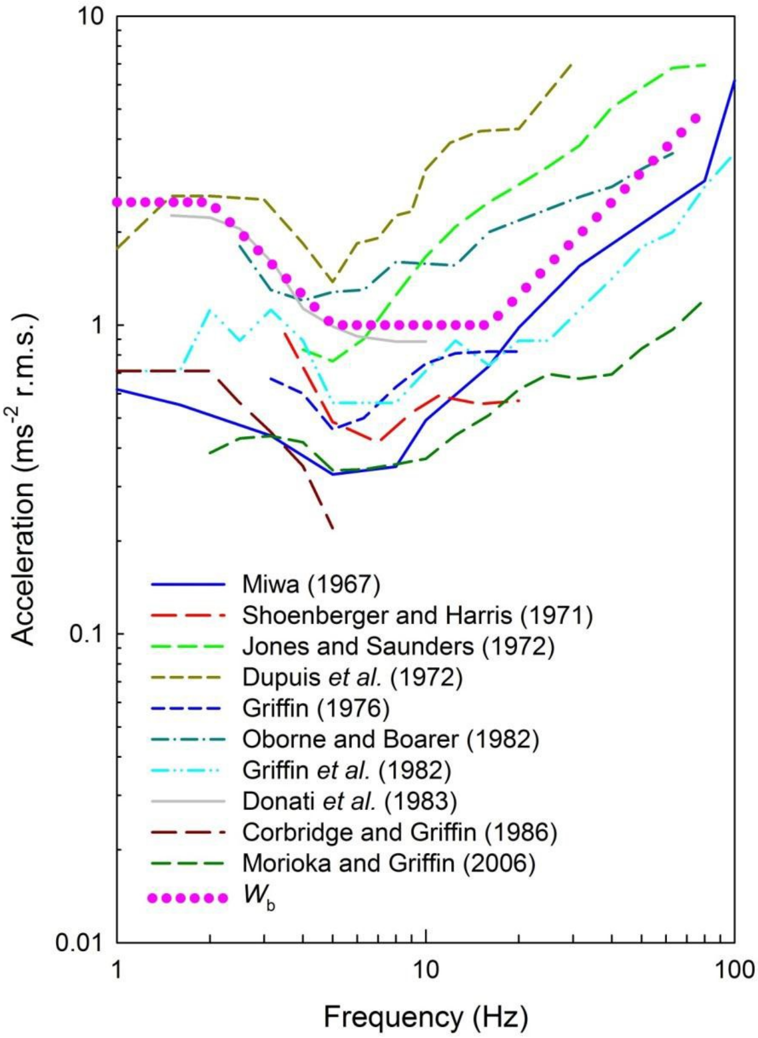

Figure 2.5 Equivalent comfort contours for vibration at the seat in the vertical direction with the inverted W_b weighting from Figure 2.7 in Basri (2012).

A consistent characteristic of the curves in Figure 2.5 is that the point of greatest sensitivity to vibration acceleration, or the lowest magnitude of acceleration necessary to achieve discomfort is around 5 Hz. This is similar to the resonance frequency of the apparent mass reported by Fairley and Griffin (1989).

These measurements involved a moving seat without a backrest and stationary feet, it is possible that the relative motion between the seat and the feet could influence the curves reported, especially at low frequencies and low magnitudes (Jang and Griffin, 1999, 2000).

2.3.4.2 Horizontal seat vibration

Unlike vertical seat vibration, discomfort caused by horizontal seat vibration is greatest at low frequencies around 1 to 3 Hz. Equivalent comfort contours across studies (Miwa, 1967; Griffin *et al*., 1982a; Corbridge and Griffin, 1986; Morioka and Griffin, 2006a; Wylie and Griffin, 2007) using different methods also show similarities (Figure 2.6).

This finding is consistent with the first and second resonant frequencies (0.7 and between 1.5 and 3 Hz respectively) of fore-and-aft and lateral apparent mass of the seated human body reported by Fairley and Griffin (1990).

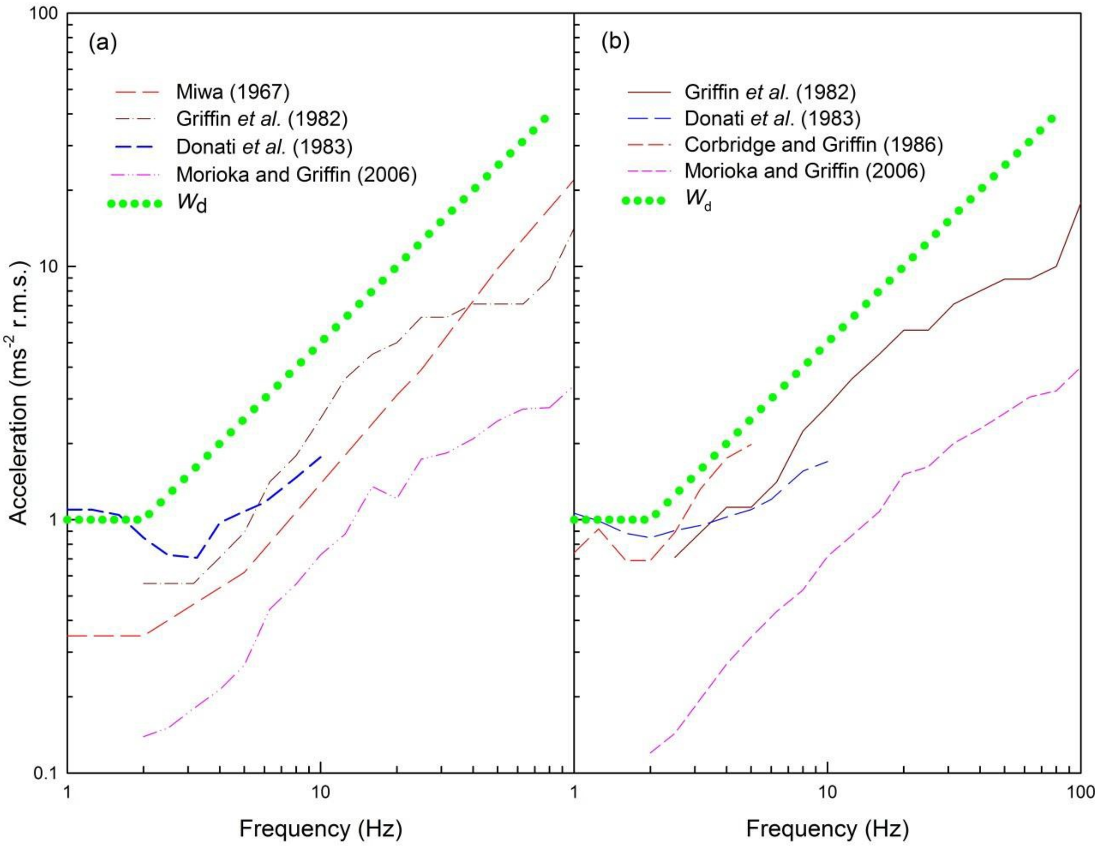

Figure 2.6 Equivalent comfort contours for vibration at the seat in the fore-and-aft (a) and lateral (b) directions with the inverted W_d weighting from Figure 2.8 in Basri (2012).

Again, these experiments involved stationary feet and a moving seat pan without a backrest and it is possible that the relative motion between the seat and the feet could influence the curves reported, especially at low frequencies and low magnitudes (Jang and Griffin, 1999, 2000).

2.3.4.3 Inter-axis equivalence

It is common in studies relating to human response to vibration discomfort to focus on one direction of motion per experiment or session. One of many reasons for this is that providing more than one axis of motion can be very complex and it is therefore more convenient to use reference motions in the same axis as the test motions. This however means that results from tests performed in different axes cannot directly be compared.

Griffin *et al* (1982a) used a 10 Hz, 0.8 ms^{-2} vertical reference motion in the method of constant stimuli for all axes and therefore discomfort levels from each direction can be directly compared. Figure 2.7 shows the inter-axis equivalence of pairs of axes (x/y, x/z, y/z) calculated by taking the ratio of the equivalent comfort contour at each frequency. In this figure, a value of x/z greater than 1 means that fore-and-aft motion caused greater discomfort at that frequency than vertical motion. Frequency weighting curves from BS 6841 (1987) are provided for reference.

Griffin and Whitham (1977) investigated dual-axis whole-body vibration discomfort from lateral and vertical motions at 3.15 Hz. Participants were able to adjust the level of lateral vibration to match the discomfort caused by seven magnitudes (0.4 to 2.5 ms^{-2} r.m.s.) of vertical vibration or adjust the level of vertical vibration to match the discomfort caused by seven magnitudes of lateral vibration. Individual responses to the motions showed more than twice the sensitivity to lateral vibrations than vertical and almost twice as sensitive to vertical as lateral at different magnitude levels, despite the standards predicting equal discomfort between vertical and lateral at 3.15 Hz. Mean regressions from both test procedures show greater sensitivity to lateral vibration at the magnitude range chosen.

Griefahn and Bröde (1997) used an intensity matching technique to obtain the inter-axis equivalence in the frequency range of 1.6 to 12.5 Hz. Subjects were instructed to adjust a horizontal motion (either fore-and-aft or lateral) to match the intensity of a vertical motion at the same frequency at one of three weighted (ISO 2631-1:1997) magnitudes (0.3, 0.6 and 1.2 ms^{-2} r.m.s.). Significant differences were found between fore-and-aft and lateral motions at all frequencies and magnitudes except for 1.6 Hz at the lowest magnitude, with greater sensitivity to fore-and-aft vibrations. Discomfort due to horizontal vibrations compared to vertical vibrations were underestimated by ISO 2631-1 (1997). The authors took steps to reduce the order bias and the duration bias of the readjustment method observed by Griffin and Whitham (1976, 1980b), although noticed that the biases of the method were present in the study.

Thuong and Griffin (2012) investigated the relative importance of fore-and-aft, lateral, and vertical vibration discomfort of standing persons at 4 Hz. It was discovered that whilst discomfort caused by fore-and-aft and lateral motions when standing are similar over the frequency range of 0.5 to 16 Hz (Thuong and Griffin, 2011) with 4 Hz vibration standing people are more sensitive to fore-and-aft vibration than lateral vibration. In addition, it was found that 4 Hz vertical vibration caused much greater discomfort relative to fore-and-aft and lateral vibration in standing people than in seated people.

It can be seen from Figure 2.7 that subjects were more sensitive to fore-and-aft vibration than lateral vibration and that subjects were more sensitive to horizontal vibration than the frequency weighting curves suggest. This means that the frequency weighting may underestimate horizontal vibration discomfort at that magnitude.

2.3.4.4 **Rotational seat vibration**

A systematic study of rotational seat vibration formed the second part of a four-part series on vibration and comfort (Parsons and Griffin, 1982; see Section 2.6.3). Similar to horizontal seat vibration, the greatest sensitivity to vibration acceleration occurred at the lowest frequencies tested.

Low frequency roll and lateral vibration discomfort, both with and without a backrest, was investigated by Wyllie and Griffin (2007). Twelve male subjects used the method of absolute magnitude estimation to determine equivalent comfort contours of lateral and roll oscillation with and without a backrest in the frequency range of 0.2 to 1.6 Hz. At frequencies below 0.4 Hz, acceleration in the plane of the seat provided a useful predictor of discomfort regardless of whether the acceleration was caused by lateral oscillation or roll through the gravity vector, above 0.4 Hz it was necessary to know whether the acceleration was due to rotation as roll caused greater discomfort than the same acceleration caused by lateral oscillation. It was concluded that at frequencies greater than about 0.4 Hz a backrest increased discomfort significantly for both lateral and roll oscillation.

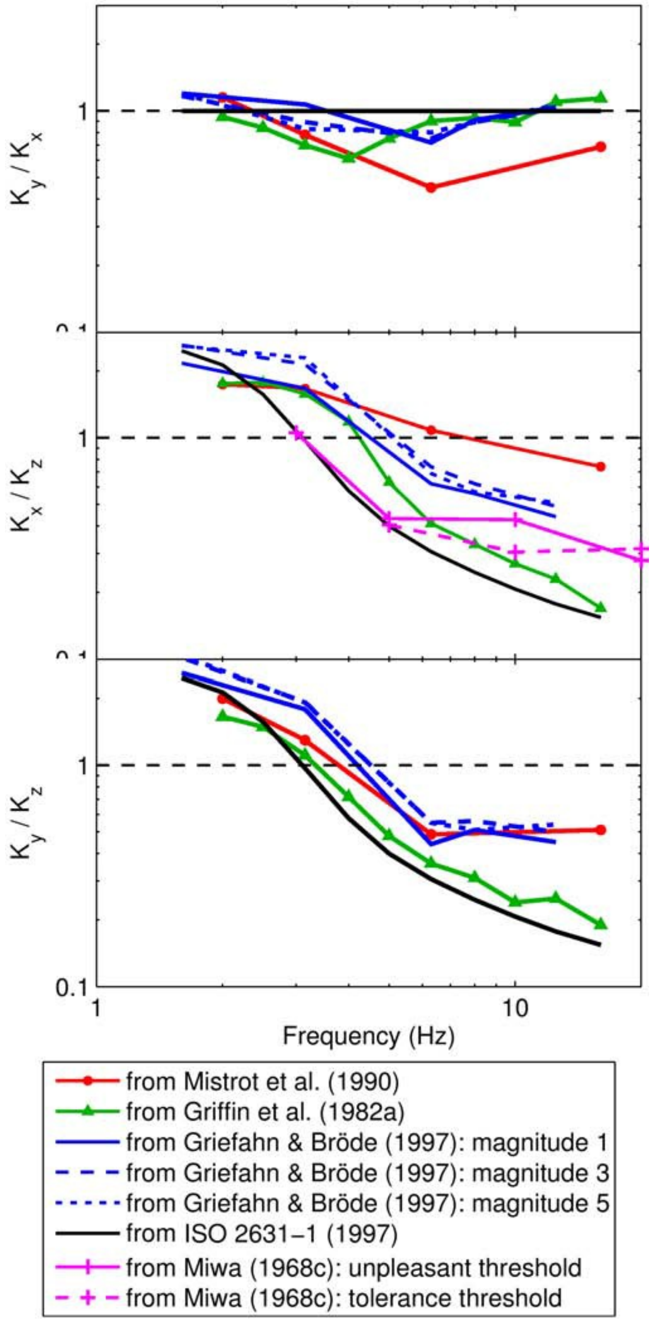

Figure 2.7 Relative sensitivity between directions of vibration derived from previous results. From Figure 2.7 in Thuong (2011)

Fore-and-aft and pitch seat vibration discomfort with and without a backrest was investigated by Wyllie and Griffin (2009). Twelve male subjects used the method of absolute magnitude estimation to determine equivalent comfort contours of pitch oscillation with and without a backrest in the frequency range of 0.2 to 1.6 Hz. It was concluded that at frequencies below about 0.63 Hz, the backrest made no difference to vibration discomfort and reduced discomfort at 0.2 Hz. At frequencies above about 0.63 Hz the backrest increased vibration discomfort significantly. At frequencies greater than 0.4 Hz with a backrest or 0.8 Hz without a backrest, pitch oscillation causing acceleration in the plane of the seat caused greater vibration discomfort than the same acceleration arising from fore-and-aft oscillation. At frequencies less than about 0.4 Hz, acceleration in the plane of the seat provided a useful predictor of discomfort.

Beard and Griffin (2013, 2014, 2016) investigated discomfort caused by lateral vibration, roll oscillation and fully roll-compensated lateral vibration in the frequency range of 0.25 to 1.0 Hz with different seat cushion and backrest conditions. For a rigid seat with a rigid vertical backrest at frequencies less than about 0.5 Hz, the lateral acceleration in the plane of the seat with the W_d weighting applied provides a useful prediction of the discomfort caused by lateral oscillation, roll oscillation and combined lateral and roll oscillation. At frequencies above 0.5 Hz, the additional contribution of the rotational acceleration is required to predict discomfort, however the root-sums-of-squares approach and using the W_e frequency weighting for the rotational component proved to be insufficient in this frequency range. Discomfort was shown to increase with roll-compensated lateral acceleration in the range from 0.5 to 1 Hz.

Foam seat cushions were shown to increase vibration discomfort at frequencies from 0.25 to 1.0 Hz. As the location of discomfort increased in the legs and lower back when sitting with a foam seat cushion, it is suggests that the cushion was causing greater postural instability during lateral and roll motions and increased muscle activity was required to maintain stability.

The presence of a backrest was shown to reduce vibration discomfort at frequencies below 1.0 Hz for lateral oscillation, below 0.63 Hz for roll oscillation and from 0.4 to 6.3 Hz for roll compensated lateral oscillation. The location of discomfort was shown to move from the ischial tuberosities with no backrest to the upper back with a full-height backrest during low-frequency lateral oscillation.

2.3.5 Magnitude

Similar to duration, it may seem intuitive that the effect magnitude has on vibration discomfort is that when magnitude is increased, vibration discomfort is increased. However magnitude has a more interesting effect.

Stevens Power Law (Equation 2.4) requires the exponent, n, known as the rate-of-growth, to calculate discomfort caused by a stimulus. If weighting curves and multiplying factors found in the British and International standards (see Section 2.6.3) are an accurate representation of human response to vibration discomfort, it would require the value of n to be the same across all frequencies and directions for the curves to be applicable at all magnitudes. However if the value of n were different for different frequencies and directions then single frequency weightings for each direction and location would not be appropriate and weightings for different magnitudes would be necessary for the accurate evaluation of vibration discomfort.

2.3.5.1 Studies suggesting no magnitude-dependence in the rate of growth of discomfort

Equivalent comfort contours produced at a wide range of magnitudes by Miwa (1967) "seem to keep parallel at equal amplitude intervals provided that the experiment could not be done at higher vibration acceleration under 3 c/s (Hz)".

Griffin *et al*., (1982a) tested the fore-and-aft, lateral, and vertical vibration discomfort of seated persons by method of constant stimuli with a reference signal at 10 Hz and magnitudes of 0.5 ms^{-2} and 1.25 ms^{-2}. The results showed only one statistically significant difference between curves obtained in the fore-and-aft axis at 4 Hz, the other results were insignificant.

2.3.5.2 Studies supporting a magnitude-dependence in the rate of growth of discomfort

The first systematic study into the effect of magnitude on the frequency-dependence of whole body vibration was by Morioka and Griffin (2006a). The first of the experiments investigated the threshold perception of 2.0-s sinusoidal seat motions in the fore-and-aft, lateral and vertical directions at the 23 preferred one-third octave centre frequencies between 2 Hz and 315 Hz using an up-down (staircase) algorithm.

Once thresholds of perception were found, the second experiment investigated rates-of-growth and equivalent comfort contours in the three translational directions in the frequency range of 2 Hz to 315 Hz, the velocity magnitude range of 0.02 to 1.25 ms^{-1} using the method of relative magnitude estimation. As threshold perception levels had already been collected, Morioka and Griffin were able to use a slight variation of Stevens' Power Law (Equation 2.6).

Rates-of-growth and values for *k* were obtained by linear regression using the logarithmic transformation of Equation 2.6:

$$\log_{10}\psi \;=\; n\log_{10}(\varphi - \varphi 0) + \log_{10}k \qquad (2.8)$$

It was found that in the fore-and-aft and vertical directions, the rate-of-growth of discomfort was highly dependent on frequency, and that the greatest exponent was around the principal resonance frequency of the human body. They concluded that '*the magnitude-dependence in the equivalent comfort contours means that no single linear frequency weighting can provide accurate predictions of subjective judgements of discomfort caused by whole-body vibration*' (Morioka and Griffin, 2006a).

This idea has since been confirmed and extended by further studies in other conditions. Wyllie and Griffin (2007, 2009) investigated seated whole-body vibration discomfort caused by fore-and-aft, lateral, roll and pitch vibration discomfort with and without a backrest in the frequency range of 0.2 to 1.6 Hz. In all cases except fore-and-aft and lateral vibration with a backrest, the rate-of-growth of discomfort, *n*, varied significantly with frequency.

Thuong and Griffin (2011a) investigated the discomfort of standing persons in the fore-and-aft, lateral, and vertical directions in the frequency range from 0.5 to 16 Hz. In both the fore-and-aft and vertical directions, the rate-of-growth of discomfort was highly dependent on the frequency of the vibration. In the lateral direction, the rate-of-growth of discomfort was independent of frequency.

Basri and Griffin (2013) investigated the discomfort of seated persons with different inclinations of backrest in the vertical direction in the frequency range from 1 to 20 Hz and W_b frequency-weighted magnitude range from 0.5 to 2.0 ms^{-2}. The rate-of-growth was highly dependent on frequency with all backrest inclinations.

Discomfort due to lateral and roll motion with different backrest conditions and at frequencies from 0.25 to 1.0 Hz was investigated by Beard and Griffin (2012, 2013, 2014, 2016). In all motion conditions, lateral, roll, and fully roll compensated lateral motion and with all backrest conditions, the rate-of-growth of discomfort was highly dependent on frequency.

The relationship between the nonlinearity in subjective and biodynamic responses to vertical vibration and shock were investigated by Matsumoto and Griffin (2005). When exposed to continuous sinusoidal vibration at 3.15 and 4.0 Hz, the normalised mechanical impedance, the normalised apparent mass, and the discomfort relative to a 5.0 Hz test vibration all increased with increasing magnitude from 0.5 to 2.0 ms^{-2} r.m.s. Relative discomfort was correlated with the normalised mechanical impedance in the frequency range of 3.15 to 8.0 Hz and relative discomfort, normalised mechanical impedance, and normalised apparent mass were correlated between 3.15 and 5.0 Hz.

2.4 Other factors affecting vibration discomfort

2.4.1 Introduction

Whilst vibration attributes are mostly encompassed by duration, frequency, direction and magnitude, there are many additional factors that can affect vibration discomfort. Whilst the majority of this literature review has concentrated on seat vibration without a backrest, seated passengers in most transport situations can experience whole-body vibration from the backrest and the floor in addition to the seat surface.

2.4.2 Input location

A systematic review of translational vibration discomfort at the feet and back, in comparison to seat comfort, was performed by Parsons *et al*, (1982) and included in a four-part series on vibration and comfort (see Section 2.6.3).

2.4.2.1 Foot vibration

For foot vibration, due to limitations of the equipment used by Parsons *et al*, (1982), an initial part of the experiment involved participants moving from one vibration for vertical seat vibration (10 Hz, 0.8 ms^{-2}) to another for foot vibration (in each of the three translational axes) also presented at 10 Hz and magnitude varying between 0.63 ms^{-2} to 8.0 ms^{-2} to determine reference foot vibration levels of equivalent discomfort to vertical seat vibration. A magnitude of foot vibration deemed appropriate was the geometric mean of the lowest level judged more uncomfortable and the highest level judged less uncomfortable than the seat vibration. These new references were then used with the method of constant stimuli to determine equivalent comfort contours for foot vibration in the three translational axes.

Discomfort of the feet was considered similar for each axis. Subjects were less sensitive to low frequency vibrations at the feet although there were limitations of the equipment. It was determined that it would be unlikely for passengers to experience low frequency vibration at the feet without associated vibration at the seat, and that the seat motion would dominate discomfort. It was however noted that further investigation was needed to consider discomfort produced by the relative phase between the seat and the feet at low frequencies.

Threshold levels, the effect of shoes, gender, and the effect of magnitude on vibration discomfort at the feet in the frequency range of 8 to 315 Hz was investigated by Morioka and Griffin (2010a). At threshold magnitude levels and frequencies below 50 Hz, the feet were more sensitive to vertical vibration than horizontal vibration and had similar sensitivity between fore-and-aft and lateral vibration. At frequencies above 63 Hz, the feet are equally as sensitive to fore-and-aft and vertical vibration and significantly less sensitive to lateral vibration.

Shoes did not affect discomfort significantly at threshold magnitudes except at 63 Hz for males and 250 Hz for females. Gender also did not have a large significant effect on discomfort at threshold magnitudes, with males slightly more sensitive than females at 31.5 Hz when wearing shoes, 125 Hz when barefoot and females more sensitive than males at 8 Hz when barefoot.

Magnitude had a large effect on the frequency-dependence of vibration discomfort. The rates-of-growth of discomfort was highly dependent on frequency in all three directions with a general trend to lower rates-of-growth with increasing frequency. Because of this, equivalent comfort contours at low and medium magnitudes (equal to half the discomfort and a similar discomfort to a 5.0 ms^{-2} r.m.s. reference motion at 50 Hz in the same direction as the test motion) show that frequency weightings W_b and W_k from the British and International standards respectively, underestimate discomfort above 16 Hz. Comfort contours equivalent to twice the discomfort of the reference motion and greater are broadly consistent with the frequency weightings in the standards. The authors suggest that because of this, '*no single frequency weighting can provide accurate predictions of discomfort caused by vibration of the foot*' (Morioka and Griffin, 2010a).

The effect of phase between the seat and the feet on discomfort was investigated by Jang and Griffin (2000). It was discovered that at frequencies less than 4 Hz and magnitudes less than 0.63 ms^{-2}, having a phase difference of 180˚ increased the perceived vibration level significantly. Above 4 Hz it was suggested that the smaller relative displacement at higher frequencies caused similar vibration perception ratings between in-phase and out-of-phase motions. Above a magnitude of 0.63 ms^{-2} it was suggested that the dominating location of vibration perception may have shifted from the legs to the torso, negating the effect of phase between the seat and feet.

The effect of thigh contact on the seat was not significant despite there being greater vibration magnitude ratings with out-of-phase with no thigh contact. It was suggested that this may be due to more effort to maintain this posture when a pitching motion is caused by the out-of-phase motions or from intermittent thigh contact causing impacts between the thighs and seat surface.

2.4.2.2 **Backrest vibration**

Parsons *et al*, (1982) also investigated vibration discomfort at the backrest. The experiment was similar to the one performed for footrest vibration and included a similar procedure for determining new reference motions at the backrest as for the footrest (Section 2.4.2.1).

It was concluded that subjects were considerably more sensitive to backrest vibration in the fore-and-aft direction than lateral or vertical. Additionally, due to the pitching motion of some vehicles and resonances in some seats, it was suggested that the fore-and-aft motion at the backrest could be greater than that at the seat or the floor of the vehicle and can sometimes become the principal location of discomfort in some situations.

Morioka and Griffin (2010b) studied the effects of fore-and-aft vibration perception with different contact points on the back and different sized contact points at different magnitudes and frequencies, see Figure 2.8.

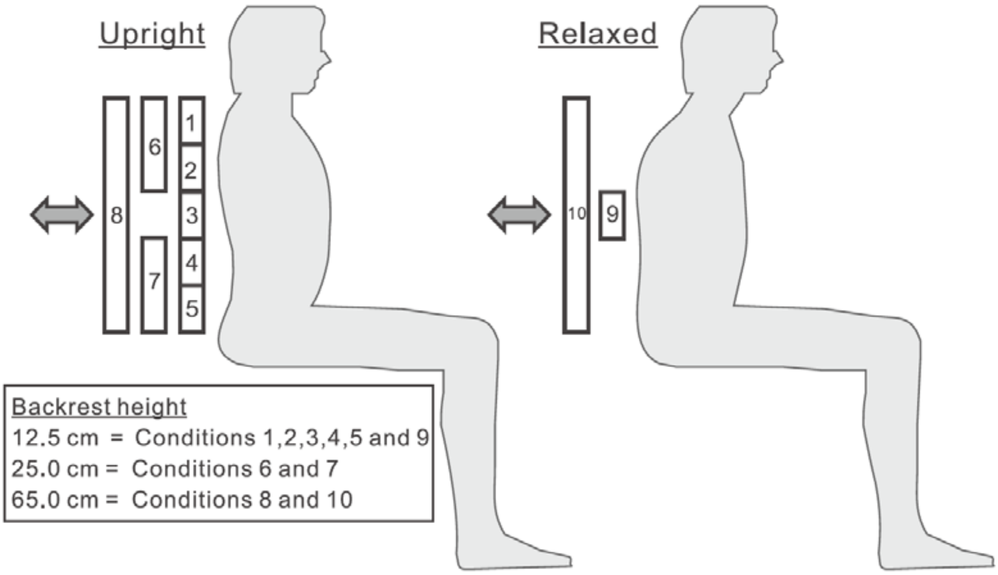

Figure 2.8 Ten backrest conditions employed in the experiment from Figure 1 in Morioka and Griffin (2010b).

It was discovered that equivalent comfort contours depend on input location of vibration. The frequency of peak sensitivity increased from 4 Hz to 8 Hz as the location of the contact with the back lowered. It was suggested that this compares well with the apparent mass of the back in the fore and aft direction determined by Jalil and Griffin (2008). The study determined that vibration at the upper back produced greater vibration discomfort than vibration at the lower back between 3 and 31.5 Hz. It was suggested that vibration at the upper back increased head movement and this could have caused the greater vibration discomfort. Vibration at the lower back was judged with greater levels of perceived vibration magnitude between 31.5 and 63 Hz, it is suggested that this could be due to increased contact force at the lower back.

Basri and Griffin (2011a,b, 2012, 2013) investigated the effect of backrest inclination on whole-body vertical vibration discomfort of seated persons. Basri and Griffin (2011a) used a rigid seat-pan and backrest mounted on a vertical shaker to investigate the effect of backrest inclination on discomfort with simultaneous vertical motion at the seat-pan and backrest. It was found that discomfort was highly dependent on backrest inclination (except between 60° and fully recumbent). Greater sensitivity was observed especially at frequencies above 12.5 Hz.

Using a backrest mounted on a shaker with stationary seat-pan, Basri and Griffin (2011b) investigated the effect of backrest inclination on backrest vibration discomfort in the direction in line with the back (i.e., vertical at 0° inclination and fore-and-aft at 90° inclination). A separate reference vibration was provided at the hand to adjust comfort contours to be equivalent, the adjusted contours did not vary significantly with inclination angle.

Basri and Griffin (2012) used a stationary backrest and moving seat-pan to investigate the effect of backrest inclination on vertical seat vibration. Participants were significantly less sensitive to motions with frequencies less than 10 Hz with increasing inclination, and most sensitive when the backrest was vertical (0° inclination).

Basri and Griffin (2013) used a rigid seat-pan and backrest mounted on a vertical shaker to investigate the effect of backrest inclination on discomfort with simultaneous vertical motion at the seat-pan and backrest. Vibration discomfort depended significantly on backrest inclination at frequencies above 5 Hz, except at 8 Hz and between the backrest inclined at 60° and when fully recumbent

2.4.3 Relative sensitivity

It is necessary for the adoption and continued use of standards and methods to evaluate vibration discomfort (as well as other areas) for the methods to be practical. In the fourth of the vibration and comfort series of papers, Griffin *et al,* (1982b) produce simplified equivalent comfort contours consisting of lines of constant acceleration and constant velocity to best fit experimental results (Figure 2.9).

It can be seen from these simplified results that some of the ‘curves’ are similar in shape across the frequency range but with an offset in magnitude. An example of this is in the lateral direction where the seat and backrest have a similar shape, particularly above 2.5 Hz, but the relative discomfort between the seat and the backrest is around 2:1. It was therefore possible to take advantage of reusing some frequency weighting curves in the standards (see Section 2.6.3) with differing multiplying factors (see Table 2.3) for the relative discomfort between input locations.

2.4.4 Location of discomfort

To understand better the nature of whole-body vibration discomfort, and what mechanisms cause differences in responses to vibration, such as variations in the rate-of-growth of discomfort, it is interesting to investigate the location where discomfort is felt within the body.

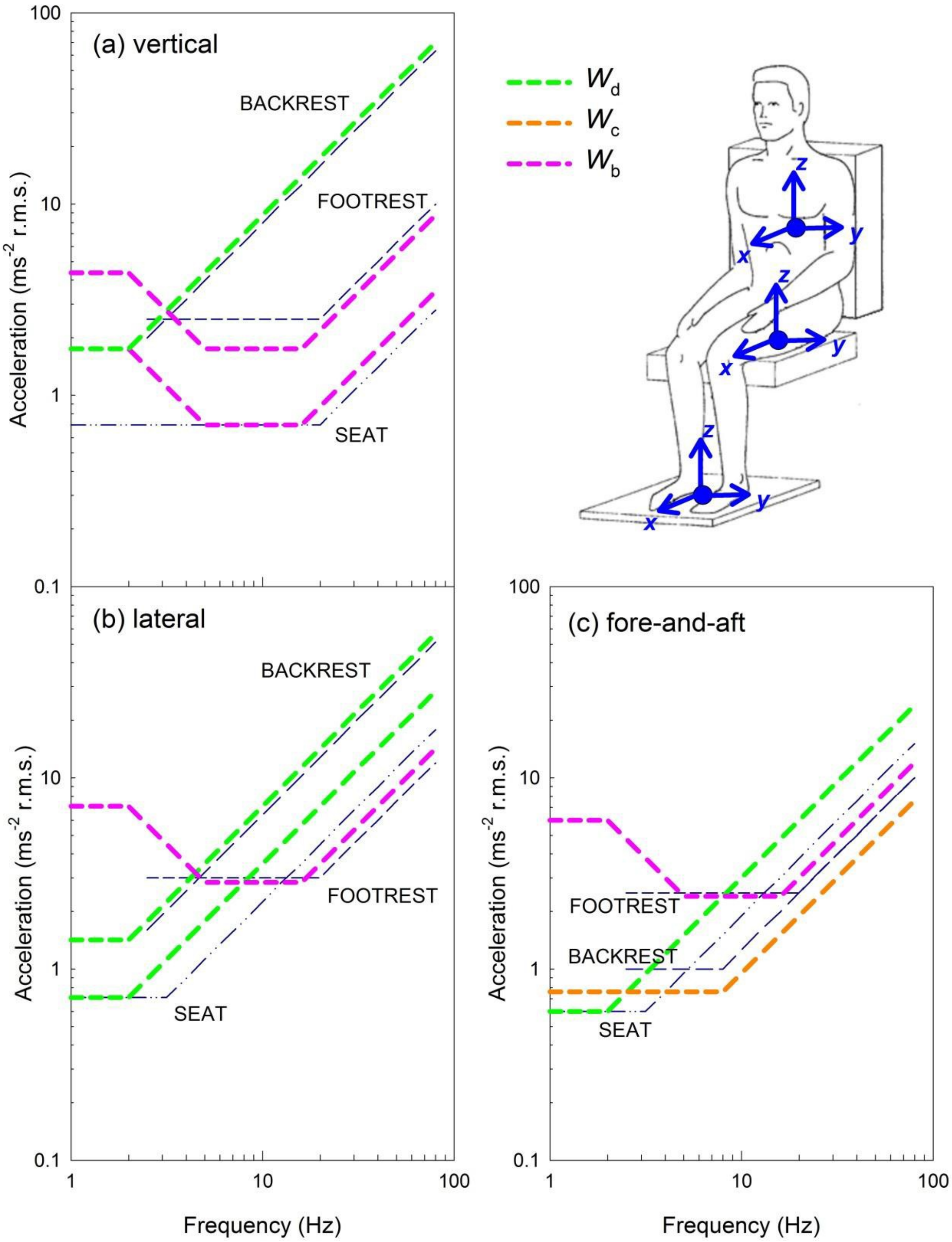

Figure 2.9 Simplified equivalent comfort contours proposed by Griffin *et al.* (1982b) to indicate the relative sensitivity to vibration at the seat, backrest and footrest in each of the translational directions of the whole body. From figure 2.10 in Basri (2012).

Frequency-dependence, direction-dependence, and magnitude-dependence of the locations of discomfort were investigated by Whitham and Griffin (1978). Participants were required to mark points on a picture of a seated person of the area causing most discomfort and areas causing any additional discomfort. The stimulus was repeated between marking the area of most discomfort and areas of secondary discomfort. Participants were exposed to vibration a 1.0 ms^{-2} in the fore-and-aft, lateral, and vertical directions at the preferred one-octave centre frequencies from 2 Hz to 64 Hz as well as vibrations in the vertical direction at 0.5 ms^{-2} and 2.0 ms^{-2} across the same frequency range.

In the fore-and-aft and lateral directions, the location of greatest discomfort was focused around the ischial tuberosities, although there was some evidence of discomfort in the front and rear lower abdomen at 8 Hz and 16 Hz. This is consistent with the discomfort being caused by shearing forces between the buttocks of the participant and the seat surface.

In the vertical direction, there was more variability across the frequency range investigated. At 2 Hz the location of most discomfort was found in the lower abdomen, travelling up the body at 4 Hz and 8 Hz, with most responses of greatest discomfort in the head at 16 Hz. Above this frequency responses became divided between the head and lower abdomen and settled towards the ischial tuberosities at 64 Hz.

Magnitude did not have a great influence over the results in vertical sinusoidal vibration. No differences were found between the motions at 0.5 ms^{-2} and 2.0 ms^{-2} except at 32 Hz where the higher magnitude caused greater discomfort in the trunk of the subjects. At both magnitudes, the general trend of location of greatest discomfort followed the same pattern as vertical vibration at 1.0 ms^{-2}.

Basri and Griffin (2011b, 2012, 2013) investigated the location of discomfort in different conditions of vertical seat-pan and backrest vibration discomfort, varying the inclination of the backrest. In conditions where only backrest motion was experienced (Basri and Griffin, 2011b) the location of discomfort was predominantly at the upper and lower back. In conditions where only the seat-pan moved (Basri and Griffin, 2012), discomfort was experienced predominantly in the thighs and buttocks, although it was noted that with an upright backrest (0° inclination) and no backrest, that discomfort was also experienced in the shoulder region as well as the lower and upper back at low frequencies, and in the neck and head at high frequencies, particularly with high magnitude vibration. Where both the seat-pan and backrest moved simultaneously (Basri and Griffin, 2013), discomfort was predominantly experienced in locations in contact with the body and in the head at high frequencies (16 and 20 Hz) with backrest inclinations of 30°, 60°, and 90°.

2.4.5 Static comfort

Whilst this thesis is concerned with the influence of vibration on discomfort, it is necessary to understand that static comfort will affect total seating discomfort. In many transport situations compliant seating is used, the material choice is usually governed by its mechanical properties including stiffness, hardness, density, etc. These properties can be optimised for typical dynamic input expected in the use of the vehicle in question to improve isolation between the vibrating surface and the seat occupant.

In addition to the dynamic performance of the seat, these factors will also influence the static comfort of the seat. Ebe and Griffin (2001) suggest that foam stiffness may be a dominant contributor to static comfort, however the relationship is not linear. Foam stiffness appeared to govern two areas of discomfort, the feeling of foam hardness and the feeling of bottoming out, where the foam is fully compressed. When the foam was very stiff, the pressure underneath the subject was not fully distributed and a foam hardness feeling dominated static discomfort. When the foam was very soft, it bottomed out and this dominated static discomfort.

Ebe and Griffin (2000) suggest a simple model (Figure 2.10) to describe the influence of both static and dynamic discomfort. It can be seen that at low dynamic discomfort, total seating discomfort may be dominated by the static comfort properties of the seat but at high dynamic discomfort, total discomfort will be dominated by the dynamic properties of the vibration input and the seat.

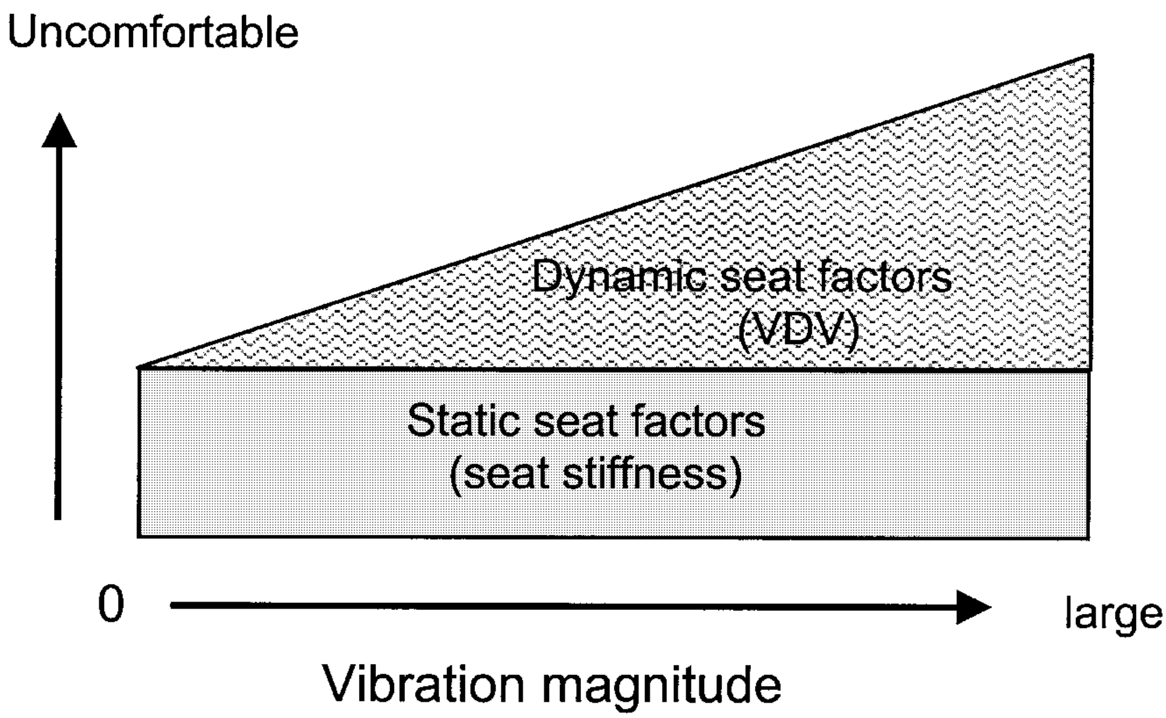

Figure 2.10 Hypothetical model for static and dynamic seat discomfort from Figure 3 in Ebe and Griffin (2000)

2.4.6 Seat Dynamics

Non-rigid seats offer static pressure relief to the seat occupant by spreading out the overall pressure. A non-rigid seat will however have a frequency-dependant transfer function when experiencing vibration. Figure 2.11 shows the transmissibilities of ten foam cushions with respect to frequency.

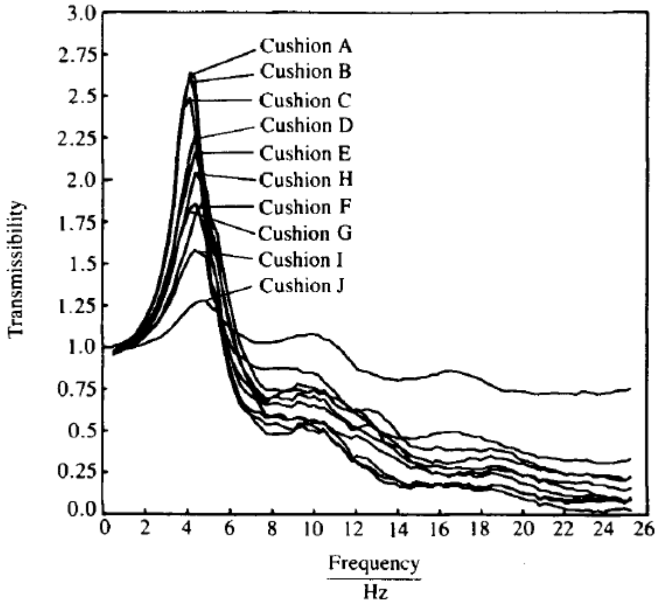

Figure 2.11 Dynamic transmissibilities of ten cushions in relation to frequency from Figure 7 in Corbridge *et al.* (1989).

It can be seen in Figure 2.11 that a soft seat can both amplify and attenuate vibration across the frequency spectrum. The amplification can exceed 2.5 times the input vibration, the resonance frequency is between 4 and 6 Hz, the higher frequencies above about 7 Hz are attenuated. A lower maximum peak at the resonance is associated with less attenuation at frequencies above the resonance.

Corbridge *et al.* (1989) determined that fitting different cushions into rail seats would offer the passenger a significantly different ride. They also stated that the ride could be significantly improved by the selection of appropriate seat materials for use in seat cushions.

2.4.7 SEAT values

One way to define the dynamic performance of a seat is with the SEAT (Seat Effective Amplitude Transmissibility) value. Published in 1978 (Griffin, 1978) and used in both ISO 10326-1 (1992) and ISO 7096 (2000) the SEAT value provides a method of giving a simple numerical value to a compliant seat cushion of its isolation efficiency. The transfer function of a seat cannot provide information on the suitability for a particular environment or about increased or decreased discomfort in relation to a rigid seat. As the SEAT value accounts for human responses to vibration discomfort through frequency weighting and should be determined with a similar vibration profile to that in which it will be used, it may be seen as providing more complete information about the suitability of a seat in a particular environment.

When determining a SEAT value it is important to provide motion similar to the environment in which the seat will be used as it is only necessary for the seat to provide isolation at the frequencies to which it will be exposed during use. If the motion applicable for the seat has low crest factors, the SEAT value is given by the equation:

$$\text{SEAT\%} = \left[\frac{G_{ss}(f)W_i^2(f)\,\mathrm{d}f}{G_{ff}(f)W_i^2(f)\,\mathrm{d}f}\right]^{1/2} \times 100 \qquad (2.9)$$

where $G_{ss}(f)$ and $G_{ff}(f)$ are the seat and floor acceleration power spectra respectively and $W_i(f)$ is the appropriate frequency weighting for the human response to vibration (as defined by the weighting on the seat for both measurements). For motions with high crest factors, the ratio between the frequency-weighted *VDV*'s from the floor and seat cushion surface is appropriate.

$$\text{SEAT\%} = \left[\frac{\text{VDV on the seat}}{\text{VDV on the floor}}\right] \times 100 \qquad (2.10)$$

The SEAT value is a percentage, where values below 100% show a decrease in vibration discomfort relative to the discomfort when sitting on the floor of the vehicle (or sitting on a rigid seat). A value of 100% suggests that that seat provides no improvement for vibration discomfort, and values over 100% suggest that the seat increases vibration discomfort compared to a rigid seat.

Non-rigid seats not only change the magnitude of vibration across the frequency range, but also the axis of the vibration and the location at which it enters the body (Griffin, 1990). Therefore, in fundamental study of human response to vibration discomfort, a rigid seat is the preferred option.

2.5 Complex motions

2.5.1 Introduction

The majority of studies concerning human responses to vibration discomfort focus on single axis, single magnitude, single frequency, sinusoidal motion, whereas most vibration experienced in outside of laboratory situations are far more complex (Griffin, 1976). Intuitively it can be seen that to understand the effect of any of the aforementioned conditions, it is necessary to reduce each stimulus of complexity and reduce the experimental variables in such a way that only the variable that is being tested changes within the experiment.

These experiments have formed the fundamental basis of understanding how each factor influences vibration discomfort individually. The accuracy of metrics for evaluating complex motion developed from experiments consisting of simple motions can be further evaluated in the laboratory by comparing discomfort caused by complex motions with predictions from metrics developed by simple motions.

2.5.2 Random motion

Griffin (1976) investigated sinusoidal and random whole-body vibration discomfort and the suitability of frequency ratings across both. Motion stimuli consisted of nine sinusoidal motions at the preferred third-octave centre frequencies from 3.15 Hz to 20 Hz, nine one-third octave bands of random motion centred at the same frequencies, three one-octave bands of random motion centred on 4 Hz, 8 Hz and 16 Hz and one three-octave band of random motion centred on 8 Hz all in the vertical direction.

The method of intensity matching was used to adjust each test motion to that of a 10 Hz, 0.75 - ms^{-2} vertical reference motion. The results show that equivalent comfort contours obtained by sinusoidal motion and one-third octave random motion was broadly similar (Figure 2.12) and that significant differences at 10 Hz and 12.5 Hz show less deviation than the inter-subject variability.

Both of these frequency weightings were applied to the results of one-octave and three-octave broadband motions. Both comfort contours performed better than the then current ISO 2631:1974 standard and both were found to be suitable for evaluating broadband motion. Whilst both were found suitable, the contour obtained using one-third octave random motion performed better.

Griffin (1976) makes mention of the crest factor applicable in non-sinusoidal motion may be of great importance when evaluating complex motions and that the measured crest factor during the experiment ranged from 4 to 8. It is possible that the results have been influenced by this property.

2.5.3 Multi-frequency vibration

Fothergill and Griffin (1977) described three experiments with vertical vibration investigating the discomfort produced by two non-harmonically matched sinusoidal motions, the discomfort produced by two motions with noticeable beating, and the discomfort produced by a combination of up to four sinusoidal motions. Three models were compared within the results of the paper, one based on the linear sum (equation 2.11), one on inhibition of the secondary component (equation 2.12) and one on the square root of the linear sum of squares (r.s.s.) (equation 2.13).

$$E_t = E_1 + E_2 \tag{2.11}$$

$$E_t = E_1 + bE_2 \tag{2.12}$$

$$E_t = (E_1^2 + E_2^2)^{1/2} \tag{2.13}$$

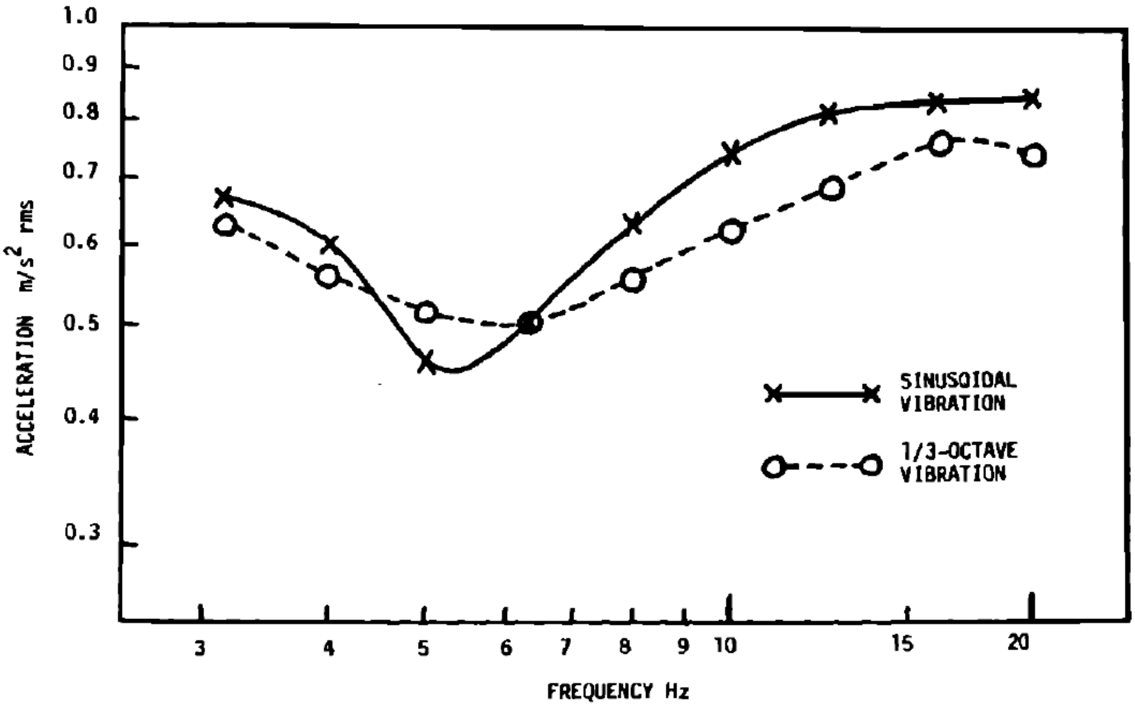

Figure 2.12 Mean levels of sinusoidal and third-octave random motion required to cause equal discomfort as 10 Hz 0.75 ms^{-2} sinusoidal vibration from Figure 4 in Griffin (1976).

The first experiment involved one of four magnitudes (0, 0.35, 0.7 and 1.4 ms^{-2} r.m.s.) of 5 Hz sinusoidal motion with either 5 Hz, 10.4 Hz, 20.4 Hz or 40 ± 1 Hz at 0.7 ms^{-2} r.m.s. Discomfort magnitudes were measured by adjusting a 10 Hz sinusoidal vertical motion until it matched the discomfort caused by the single or dual-frequency test motion.

In the second experiment, the discomfort of eighteen dual-frequency motions with noticeable beatings as well as the single-frequency components (integer sinusoids between 3 Hz and 35 Hz at 0.7 ms^{-2} r.m.s.) using the same method as the first experiment. The beating nature of the motions was produced by combining the single frequency sinusoids with a 20 Hz sinusoidal motion at 0.7 ms^{-2}. The 'beating' was felt as short bursts of vibration when the frequency of the two sinusoids were close, between about 12 Hz to 27 Hz. The third experiment consisted of sinusoidal motions at 5 Hz, 11 Hz, 23 Hz and 35 Hz and magnitudes of 0.7 and 1.4 ms^{-2} as well as combinations of these motions.

It was discovered that the 'worst component' method (equation 2.11) then recommended in an ISO standard (ISO 2631:1974) was a very poor predictor of vibration discomfort, as was the linear sum of vibration magnitudes. The other two methods were found to be reasonable predictors of vibration discomfort, with the root-mean-square (r.m.s.) method (similar to equation 2.13) being favoured because it was easy to apply electronically.

2.5.4 Multi-axis vibration

When evaluating ride comfort in a vehicle, a single discomfort rating is advantageous for a complex system, especially when comparing the ride comfort of multiple vehicles. The British standard (BS 6841:1987) suggests the reporting of each axis and location individually, but allows for the root-sums-of-squares (r.s.s.) to additionally be reported for an overall ride value.

An experiment was designed by Griffin and Whitham (1977) to measure the discomfort caused by combined 3.15 Hz lateral and vertical motion. The experiment was run in two parts using the method of adjustment. In one part, subjects adjusted a 3.15 vertical test vibration until it caused similar discomfort to ten different dual-axis motions comprised of five combinations of different magnitude lateral and vertical 3.15 Hz sinusoidal motion at either 0° or 90° phase difference. As the frequency of this motion was the same in each axis, this phase difference causes either an "up-right, down-left" translational motion or an anti-clockwise circular motion.

In the second part of the experiment, subjects adjusted a 3.15 Hz vertical vibration until it matched the discomfort of seven different magnitudes of lateral 3.15 Hz vibration (0.4, 0.52, 0.7, 1.0, 1.4, 2.1 and 2.5 ms^{-2}) as well as matching lateral 3.15 Hz vibrations to the same magnitudes of vertical vibration.

It was found that discomfort did not depend on the relative phase of the dual axis stimuli. In addition to this, the worst component method, a masking method and the root-mean-square of equivalent magnitudes were tested as prediction methods for dual-axis vibration (the masking method and r.m.s. method are equivalent to equations 2.12 and 2.13 respectively). The worst component method consistently underestimated dual-axis discomfort as expected by an error of up to 40%. Using the mean value in the masking method (b = +0.21 for the vertical test and b = +0.16 for the lateral test motion) predicted levels with errors up to 6%, although the results were not significantly different from the measured results. The r.m.s. method produced errors up to 10%, three of which were significant, however it was concluded that for the practicalities of applying the method to evaluate ride comfort the r.m.s. method was recommended.

Mistrot *et al.* (1990) performed a similar experiment using the same frequency in each direction at both 3.15 Hz and 6.3 Hz for combinations of fore-and-aft and vertical and lateral and vertical dual-axis motions. Using only integer values in equation (2.13) it was found that an exponent of 2 (or r.s.s.) provided the least difference in the results, with lower values overestimating and higher values underestimating discomfort.

Fairley and Griffin (1988) used many sinusoidal motions in different combinations from 2.5 Hz to 10 Hz in the vertical and fore-and-aft directions to determine discomfort caused by dual-axis motion. It was found that an exponent of 2.07 used in a power summation was optimum, suggesting that an r.s.s. approach was reasonable. There were some significant differences between the experimental results and those obtained by an r.s.s. summation, however this may be explained by noticeable 'beating' in the stimuli caused by the phase of two sinusoids used resulting in Lissajous' type patterns.

The above methods used an objective magnitude estimate rather than a subjective one, therefore if similar experiments were performed using subjective estimation methods, it is reasonable to assume that the value concluded in the power summation method (equation 2.13) may differ.

Thuong and Griffin (2015) investigated the discomfort of standing persons caused by multi-axis octave-band filtered random vibration centred on 1 Hz and 4 Hz. Using the method of relative magnitude estimation, subjects provided a number that reflected the discomfort produced by either single, dual- or tri-axial motion compared to a tri-axial reference motion at the same frequency of the test (either 1 Hz or 4 Hz) assuming that the reference motion had a magnitude of '100'.

Optimal values for use in a power summation were determined at 2.7 for motion centred on 1 Hz and 3.0 for motion centred on 4 Hz. The average of these two values, 2.85, was within the suitable range for both frequencies and so an overall value for the power of 2.85 was chosen for a power summation method. They also considered the rate-of-growth of discomfort, *n* in Stevens' Power Law, suggesting that the value of α would be affected by the rate-of-growth of discomfort and a new value, β, is the power summation value:

$$\psi_{total} = (\psi_a^{\beta/n} + \psi_b^{\beta/n})^{n/\beta} \qquad (2.14)$$

$$\alpha = \frac{\beta}{n} \qquad (2.15)$$

When using equation 2.15, it was noted that the using the average rate-of-growth for standing humans, 0.72 (Thuong and Griffin (2011), and the optimal value of α, 2.85, that the value of β is 2.05 which is very similar to the use of 2 found useful in previous studies mentioned. It was suggested that the value of *β* would depend on the frequency and direction of the motion although there were no comparisons made using different values of *n* in the paper.

2.5.5 Multi-input vibration

The above studies of either simple or complex motions focus mainly of whole-body vibration from a single input (the seat, the backrest, the floor etc.) and do not consider combining the multiple inputs of vibration. In a paper following the four-part series on Vibration and Comfort (see section 2.6.3) Parsons and Griffin (1983, see Section 2.6.2) included the inputs from multiple locations of the seat-human interface when evaluating different methods of predicting vibration discomfort in a complex environment. It was concluded that the r.s.s. method of combining multiple input locations, as well as multiple axes was the most efficient prediction method.

Jang and Griffin (2000) investigated the effect of phase and posture of discomfort caused by sinusoidal vertical vibration at the seat and the footrest. Twelve healthy male subjects took part in the experiment over three sessions experiencing motions in the frequency range of 2.5 to 6.3 Hz and the magnitude range of 0.16 to 1.6 ms^{-2}. It was concluded that out of phase motions at the seat and the footrest caused greater discomfort, in general, and that the effect was more pronounced at the lower frequency range and lower magnitude range of the experiment. The effect of the phase decreased at frequencies above 5 Hz, also decreasing at magnitudes above 0.63 ms^{-2}.

2.6 Predicting vibration discomfort

2.6.1 Introduction

One of the driving forces in attempting to understand the effects of vibration discomfort is to try to be able to predict vibration discomfort based upon measurements or simulations of vibration environments. Vibration enters the human body in different directions, at different magnitudes across a wide frequency range across the entire surface of the seat-human interface, making it virtually impossible to measure the complex motion at each point that the human transducer will feel it. Therefore, there must be some compromise between the ‘perfect’ method to evaluate discomfort and a practical method.

Differing methods listed below have slowly evolved based on improved understanding of vibration discomfort and increased availability of measurement devices and processing power.

2.6.2 ISVR 1983

Parsons and Griffin (1983) evaluated nine different methods of evaluating vibration discomfort in vehicles based upon twelve measured vehicle vibration inputs at three locations and passenger discomfort responses. The nine methods for evaluating the vibration discomfort were based upon three weighting methods and three combining methods.

The three weighting methods consisted of the weighted maximum frequency level ($w_{max}f$), the weighted r.m.s. level (w_{rms}) and the weighted r.m.q level (w_{rmq}). The three different combining methods were the most severe component (MSC), root-sums-of-squares (r.s.s.) and root-sums-of-quads (r.s.q.).

The twelve vibration inputs at three locations can be seen in Figure 2.13. These involved the three translational axes at the seat (fore-and-aft, lateral, and vertical), three rotational axes at the seat (roll, pitch and yaw) as well as the same translational axes at the backrest and the floor. These inputs were weighted and then combined using the methods described above for the model shown in Figure 2.14.

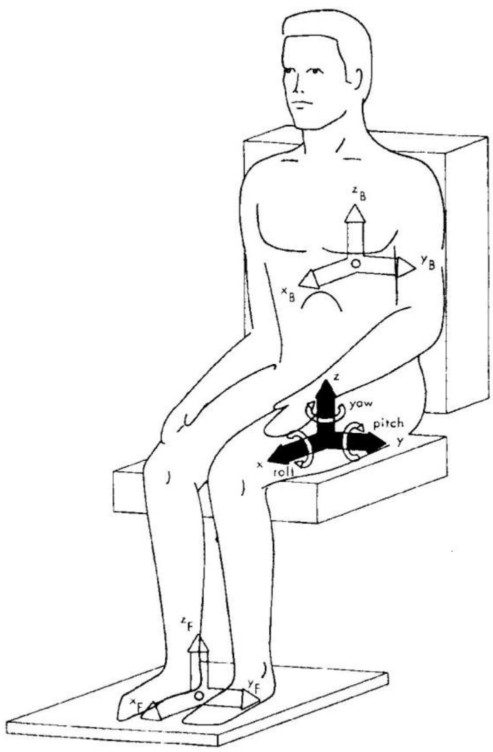

Figure 2.13 Twelve axes recommended by the standards for comfort of seated persons from Figure 2 in Parsons and Griffin (1983).

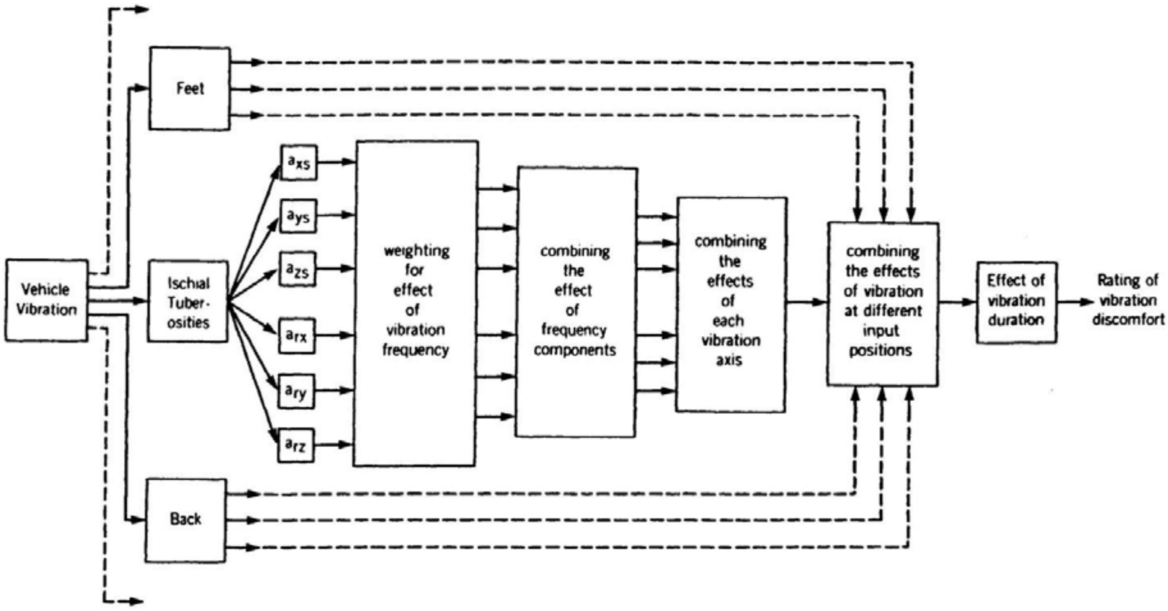

Figure 2.14 From Figure 1 in Parsons and Griffin (1983), a model for predicting discomfort of seated passengers which were later adopted in the current standards.

Measurements taken from all twelve inputs using appropriately mounted accelerometers were then evaluated by each of the nine methods of weighting and combining to give a single discomfort score for each of twelve vibration inputs comprised of different road types from rough to smooth and driving speeds from 10 to 55 mph.

Discomfort scores were given by each subject by marking a position on a 100 mm line to describe the level of discomfort experienced. A key was given at each end of the line marking “little discomfort” and “much discomfort”.

The efficiency of each method was evaluated and ranked. The method evaluated as the best was the frequency weighted r.m.s. method for summation within an axis and the r.s.s. method for summation between axes. It was clearly shown that using only the ‘worst’ component of the frequency spectra and the ‘worst’ input would not be the optimum prediction method, although it was noted that the weighted r.m.s. was known to underestimate vibration severity when the crest factor is high. It was recommended that the r.m.q. method be used for summation within an axis when crest factors are high, despite noting that it did not perform well for two of the six vehicles chosen. For the conditions chosen within the experiment r.m.s. averaging seemed sufficient.

2.6.3 Current techniques (BS 6841:1987 and ISO 2361-1:1997)

There are two available standards in the UK that detail methods to measure and evaluate vibration input to a passenger, the British Standard BSI 6841 (1987) and the International Standard ISO 2631-1 (1997).

To understand better the procedures described and recommended within the standards, it is important to know where the recommendations are coming from. A four-part series of papers titled "Vibration and comfort" comprised of six experiments influenced decisions made about frequency weightings, axis and location multiplying factors, measurement locations, time averaging and axis combination methods. In addition to the four papers, an extensive review of the existing literature provided solutions for summation over axes (see Sections 2.5.3 – 2.5.5), the use of r.m.q. averaging and time-dependency (see Section 2.3.2). Further research was also required for low-frequency comfort contours (see Section 2.6.3.5).

2.6.3.1 Vibration and comfort I. Translational seat vibration

The first paper of the series is concerned with translational seat vibration. Griffin *et al.* (1982a) conducted two experiments to quantify the effect of magnitude and frequency on human responses to translational seat vibration discomfort. This paper also gives an overview of the four-part series.

Twelve male volunteers took part in the first experiment focussing on the effect of magnitude on vibration discomfort. The method of constant stimuli was employed in this experiment and to reduce the 'order effect' observed by Griffin and Whitham (1980a) the order of presentation was 'reference' - 'test' - 'reference' - 'test'. Subjects had no control over the magnitude or duration of the signal and answered with a box containing three response buttons, indicating whether the first or the second motion caused most discomfort or whether the subject wanted the motions to be repeated. The order of the presentation of stimuli was randomised independently for each subject and each session and computer controlled, with stimuli removed for being assumed to be either too high or too low in magnitude based on the subjects' response.

Vibration was produced on a rigid plate used as a seat surface without a backrest at the preferred seven octave centre frequencies from 1 to 63 Hz, with both reference and test stimuli lasting 4 seconds. Comfort contours equivalent to 0.5 ms^{-2} and 1.25 ms^{-2} 10 Hz vertical vibration were obtained for motions in each of the three axes across six sessions, each session corresponding to one direction and one reference magnitude. The equivalent level at each frequency was determined from the geometric mean of the highest level of the test motion considered less uncomfortable than the reference, and the lowest level considered more uncomfortable than the reference.

It was concluded that effects of magnitude within subjects was small compared with the differences between subjects over the magnitude range investigated. It was suggested that some non-linearity may cause differences at higher and lower levels than investigated, but for the range covered it seemed reasonable to determine a single equivalent comfort contour in each axis.

Eighteen males and eighteen females participated in the second experiment conducted to determine the effect of vibration frequency in each of the translational directions. Using the same method as the first experiment, subjects were required to respond to test motions compared with a 0.8 ms^{-2} r.m.s. 10 Hz vertical motion. Subjects responded with a choice of three buttons as stated in the previous experiment. Subjects attended six sessions (this experiment was combined with a similar one for rotational motion, see Section 2.6.3.2), the order of presentation of axis was determined by three 6 x 6 Latin squares within both the group of male and the group of female subjects.

Motions consisted of sinusoidal translational vibration at the 21 preferred one-third octave centre frequencies from 1.0 to 100 Hz and discrete magnitudes in the logarithmic sequence of 0.1, 0.125, 0.16, 0.2, …, 12.5, 16.0, 20.0 ms^{-2} r.m.s. although it was reported that it was not necessary to present more than eight discrete levels to each subject as unnecessary stimuli were removed by the computer controlling the stimuli based on the answers given by subjects.

It was concluded from this paper that discomfort depends on the frequency of translational vibration of a supporting seat surface and that a magnitude range of 2.5:1 had little effect on the frequency-dependence of discomfort. Comfort contours equivalent to 0.8 ms^{-2} r.m.s. 10 Hz vertical vibration were determined for each of the one-third octave centre frequencies from 1 to 100 Hz in the fore-and-aft, lateral and vertical directions.

2.6.3.2 Vibration and comfort II. Rotational Vibration

The second paper in the series was concerned with rotational seat vibration. Parsons and Griffin (1982) conducted two experiments to quantify the effect of magnitude and frequency on human responses to rotational seat vibration discomfort.

In the first of two experiments, twelve male subjects participated. Subjects attended three sessions, comfort contours for roll and pitch were obtained across the first two sessions and contours for yaw were obtained in the third session, the presentation of the directions within the first two sessions and of the magnitude in the third session was balanced.

At the beginning of each session concerned with roll vibration, the subjects were first required to compare the 10 Hz vertical reference motion of either 0.5 ms^{-2} or 1.25 ms^{-2} r.m.s. with various magnitudes of 10 Hz roll vibration. This was necessary as for this procedure subjects had to move between two vibrators setup for either vertical or roll vibration and moving between vibrators was unwanted for the rest of the experiment. Each vibrator used a rigid plate for a seat surface with no backrest. An equivalent 10 Hz roll vibration was determined as the geometric mean of the lowest magnitude considered more uncomfortable than the vertical reference and the highest level considered less uncomfortable than the vertical reference. The resulting motion was then used as the new reference for the rest of that part of experiment for that subject. The same procedure was necessary for pitch vibration but not for yaw vibration as the seat on which the subjects sat could be moved in both the vertical and yaw axes.

Following the initial setup of a rotational reference motions, subjects determined equivalent comfort contours using the same process as the two experiments in the first part of this series. The frequency range for this part of the experiment was from 1.0 to 31.5 Hz with vibrations at each of the six octave centre frequencies within this range.

Similar to translational vibration it was determined that over the 2.5:1 magnitude range covered in this study the difference in shape of the contours of equivalent discomfort were generally small compared to differences between individuals and therefore a single equivalent comfort contour should be reasonable within the range covered.

The second experiment was conducted together with the second experiment of part one and used similar methods. Eighteen males and eighteen females took part in the experiment. New reference levels for both roll and pitch motion were determined using the same method as above and a 0.8 ms^{-2} r.m.s. 10 Hz vertical reference vibration, yaw vibrations were directly compared with a 0.8 ms^{-2} r.m.s. vertical vibration.

Test motions consisted of sinusoidal rotational motion at the 16 preferred one-third octave centre frequencies from 1.0 to 31.5 Hz in roll and pitch axes and the 14 preferred one-third octave centre frequencies from 1.0 to 20 Hz in the yaw axis.

It was concluded from this paper that discomfort depends on the frequency of rotational vibration of a supporting seat surface and that a magnitude range of 2.5:1 had little effect on the frequency-dependence of discomfort. Comfort contours equivalent to 0.8 ms^{-2} r.m.s. 10 Hz vertical vibration were determined for each of the one-third octave centre frequencies from 1 to 31.5 Hz in the roll and pitch directions and from 1 to 20 Hz in the yaw direction.

2.6.3.3 Vibration and comfort III. Translational vibration of the feet and back

The third paper in this series in concerned with translational vibration at the feet and the back. Parsons *et al.* (1982) conducted two experiments to quantify the effect of frequency on foot vibration and backrest vibration of seated subjects.

Twelve male subjects took part in the first experiment regarding foot vibration. The experiment was conducted to determine discomfort caused by foot vibration for seated subjects in the three translational axes over the frequency range of 2.5 to 63 Hz (2.5, 4, 8, 16, 31.5 and 63 Hz) equivalent to 0.8 ms^{-2} r.m.s. 10 Hz vertical seat vibration.

Subjects attended three sessions, one for each axis, and the presentation order of the axes of vibration were determined by four 3 x 3 Latin squares for the twelve subjects. At the beginning of each session, a process similar to that used for roll and pitch vibrations was necessary. Subjects moved between two vibrators set up to produce vertical seat vibration and either fore-and-aft, lateral or vertical foot vibration, depending on the session. Subjects were required to determine a 10 Hz foot vibration of equivalent discomfort to a 0.8 ms^{-2} r.m.s. 10 Hz vertical seat vibration. Once an equivalent foot vibration was determined, it was used as the reference motion for the rest of that particular session to avoid the subject moving between vibrators.

It was concluded that the sensitivity of the feet is similar in all axes and the contours suggest greatest sensitivity to acceleration around 20 Hz. At low frequencies, excitation of the feet causes much less discomfort than excitation of the seat at the same frequencies, at higher frequencies the feet become relatively more sensitive.

Twelve male subjects took part in the second experiment concerning backrest vibration. The experiment was conducted to determine discomfort caused by backrest vibration in the three translational axes over the frequency range of 2.5 to 63 Hz (see above) equivalent to 0.8 ms^{-2} r.m.s. 10 Hz vertical seat vibration.

Subjects attended three sessions, one for each of the axes investigated. Each session was run in a similar manner described for the foot vibration experiment, with subjects determining a 10 Hz backrest reference motion equivalent to 0.8 ms^{-2} r.m.s. 10 Hz seat motion by moving between two vibrators and running the rest of the experiment with the new backrest reference motion.

It was concluded that lateral and vertical sensitivity at the backrest was relatively similar, but both the magnitude and the shape of the equivalent comfort contour in the fore-and-aft direction differed greatly. An example is given around 8 Hz where lateral and vertical motion would have to be between five and ten times greater to cause equivalent discomfort.

As mentioned before (see Section 2.4.2.2) one main conclusion of this paper was that the pitching motion of some vehicles and the resonances in some seats may cause the fore-and-aft motion at the backrest greater than that at the seat pan or the floor. High sensitivity of fore-and-aft backrest motion determined in the second experiment suggests that this area may become the principal source of vibration discomfort in some vehicles.

2.6.3.4 Vibration and comfort IV. Application of experimental results

The fourth and final paper in the series is concerned with the application of the experimental results within the series. Griffin *et al.* (1982b) offer a summary of the experiments conducted and an interpretation of the results. A comparison is made between the current results and previous results with justifications for differences.

Determining equivalent comfort contours in all twelve axes (fore-and-aft, lateral and vertical at the seat, feet and backrest and roll, pitch and yaw at the seat) is described as the principal objective of these studies. An argument is made for simplified equivalent comfort contours consisting of slopes having multiples of 6 dB per octave (equivalent to constant acceleration or constant velocity) and 'corner' frequencies at preferred one-third octave centre frequencies. A comparison between the simplified contours and the median and interquartile data from the experiments is shown in Figure 2.15. It was noted that the simplified contours generally fell within the interquartile range of the experiment.

A method of weighting and time averaging complex motions is described based on Griffin (1976) to frequency weight each axis and use the r.m.s. values obtained. A method to combine the 12 axes of vibration is recommended based on the root-sums-of-squares approach taken from Parsons and Griffin (1978). A suggestion is made to use the root-mean-quad (r.m.q.) where vibration time histories contain impulsive vibration and shocks with high peaks as suggested by Griffin and Whitham (1980a) and that the r.m.q. defines a long-term time-dependency of human response to vibration than that defined by r.m.s. (Griffin and Whitham, 1980b).

Sensitivity to foot vibration is shown to be much lower than that of seat vibration at low frequencies and will only become a significant source of discomfort at high frequencies where attenuation of vibration can occur in the seat. Sensitivity to fore-and-aft vibration at the backrest is greater than that of fore-and-aft vibration at the seat at frequencies above about 5 Hz and therefore vibration in this location can become a principal source of vibration discomfort. In practice, due to resonances within the seat and the pitching potion of some vehicles, the magnitude of fore-and-aft vibration at the backrest can be greater than that at the seat surface and further increase the importance of backrest vibration.

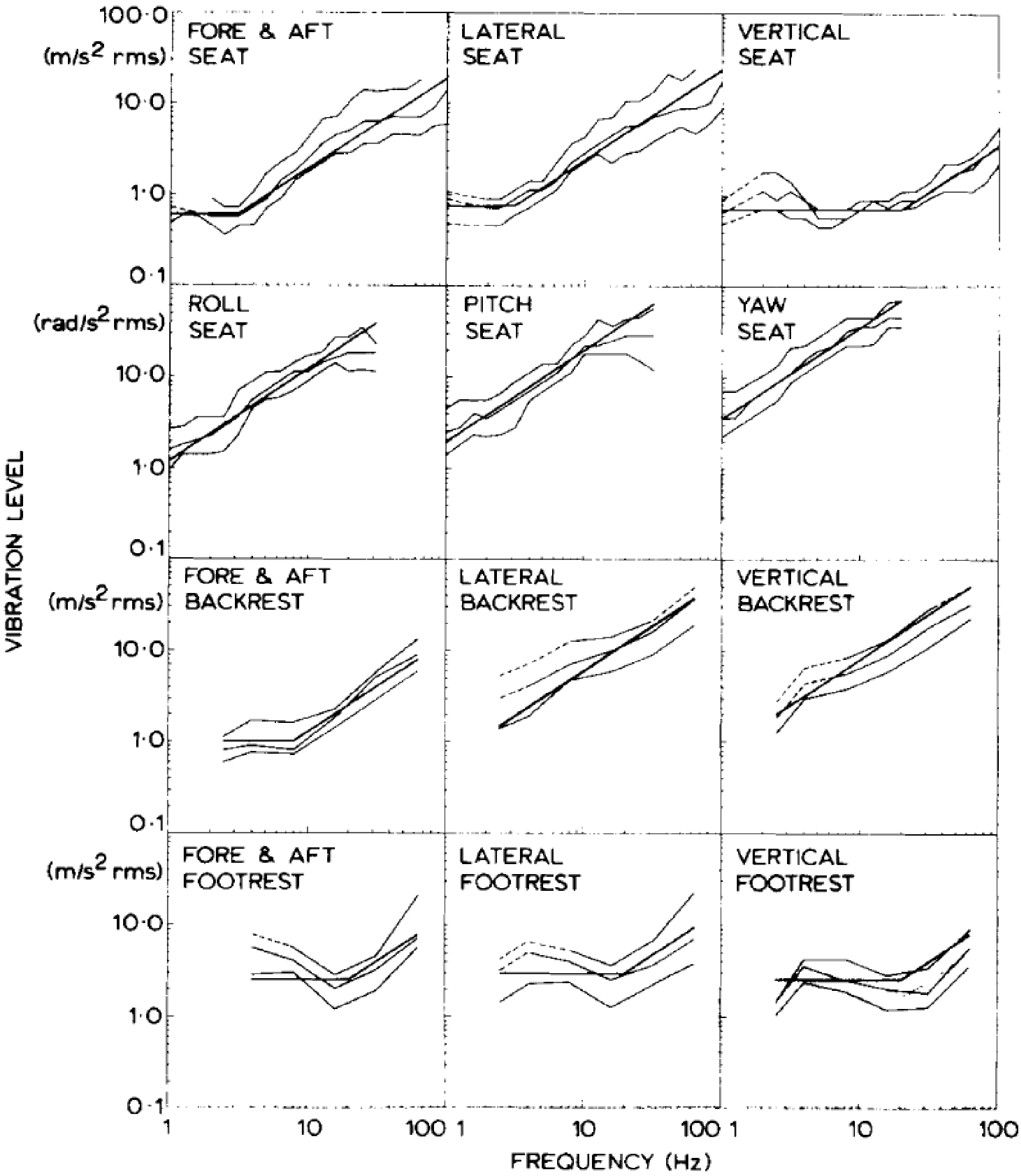

Figure 2.15 Median and inter-quartile ranges of equivalent comfort contours with suggested simplified contours for all axes of seated persons from Figure 5 in Griffin *et al.,* (1982b)

For convenience, weighting contours equal to the reciprocal of the simplified comfort contours were constructed such that 10 Hz vertical seat motion has a value of 1.0. The simplified weightings are shown in Figure 2.16 and described in Table 2.2.

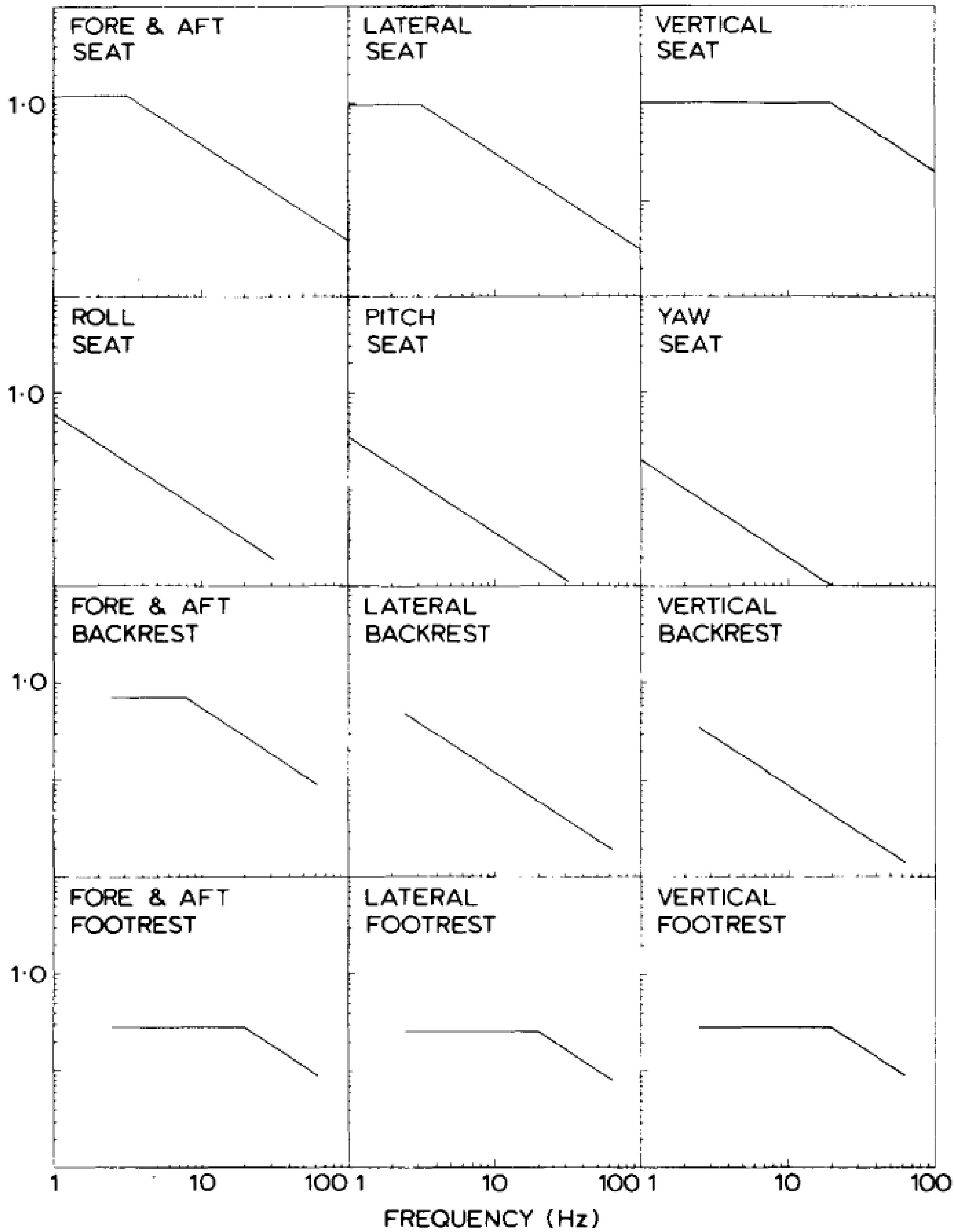

Figure 2.16 Simplified frequency weightings proposed by Griffin *et al*., (from figure 6 in Griffin *et al*., 1982b) based on the reciprocal of the simplified equivalent comfort contours.

Table 2.2 Equations for weighting curves (W = weighting level: f = frequency of vibration (Hz)) (Griffin *et al.,* 1982b).

			Seat		
a_x	If	1.0	$\leq f \leq$	3.15	$W = 1.2$
	If	3.15	$< f \leq$	100	$W = 3.8/f$
a_y	If	1.0	$\leq f \leq$	3.15	$W = 0.95$
	If	3.15	$< f \leq$	100	$W = 3.0/f$
a_z	If	1.0	$\leq f \leq$	20.0	$W = 1.0$
	If	20.0	$< f \leq$	100	$W = 20/f$
r_x	If	1.0	$\leq f \leq$	31.5	$W = 0.6/f$
r_y	If	1.0	$\leq f \leq$	31.5	$W = 0.35/f$
r_z	If	1.0	$\leq f \leq$	20.0	$W = 0.2/f$
			Feet		
a_x	If	2.5	$\leq f \leq$	20.0	$W = 0.28$
	If	20.0	$< f \leq$	63.0	$W = 5.6/f$
a_y	If	2.5	$\leq f \leq$	20.0	$W = 0.25$
	If	20.0	$< f \leq$	63.0	$W = 5.0/f$
a_z	If	2.5	$\leq f \leq$	20.0	$W = 0.28$
	If	20.0	$< f \leq$	63.0	$W = 5.6/f$
			Back		
a_x	If	2.5	$\leq f \leq$	8.0	$W = 0.7$
	If	8.0	$< f \leq$	63.0	$W = 5.6/f$
a_y	If	2.5	$\leq f \leq$	63.0	$W = 0.875/f$
a_z	If	2.5	$\leq f \leq$	63.0	$W = 0.875/f$

All three axes of rotational motion have greatest sensitivity at 1 Hz, even at this frequency if a person sits about 1 meter or more from the centre of rotation their discomfort will be dominated by the resulting translational motion and at higher frequencies the translational motion will dominate from less distance from the centre of rotation. Equivalent comfort contours of rotational motion are therefore restricted to the area directly under the ischial tuberosities. Rotational vibrations may be a major source of vibration discomfort by either the rotational component itself or the resulting translational motion due to rotation.

A comparison is made between the method suggested within the paper and that of ISO 2631 (1978). Evidence is given that axes of vibration other than that of translational seat vibration may be the dominant cause of discomfort (Parsons and Griffin 1980), the ISO procedure also underestimates relative discomfort due to vertical vibration above 8 Hz and is therefore insufficient. The numerical methods from the ISO standard are challenged and the necessity for the laboratory experiments demonstrated.

The new method proposed within the standard provides powerful predictive power due to the complexities of the procedure for design purposes. However this may be simplified for particular applications if there is sufficient knowledge of the system it is applied to.

2.6.3.5 Other studies that influenced the standards

The vibration and comfort papers did not cover all aspects necessary to create the standards. One aspect not covered is frequency dependency below 1 Hz. Corbridge and Griffin (1986) investigated the discomfort caused by low-frequency whole-body vertical and lateral motion.

Forty participants (twenty male and twenty female) took part in the first experiment focussing on the effect of frequency on vertical vibration discomfort. The method of constant stimuli was employed in this experiment and the order of presentation was ‘reference’ - ‘test’ - ‘reference’ - ‘test’. Vibration was produced on a 1-meter stroke vertical hydraulic vibrator and participants sat on a rigid wooden seat with an upright backrest, the participants’ feet rested on the vibrator and moved in unison with the seat. Vibrations were produced at the preferred eleven one-third octave centre frequencies from 0.5 to 5 Hz, with both reference and test stimuli lasting 10 seconds. Comfort contours equivalent to 0.25 ms^{-2} and 0.75 ms^{-2} 2-Hz vertical vibration were obtained for motions in the vertical axis across two sessions, each session corresponding to one reference magnitude. The equivalent level at each frequency was determined from the geometric mean of the highest level of the test motion considered less uncomfortable than the reference, and the lowest level considered more uncomfortable than the reference.

Subjects had no control over the magnitude or duration of the signal and answered with a box containing three response buttons, indicating whether the first or the second motion caused most discomfort or whether the subjects wanted the motions to be repeated. The order of the presentation of stimuli was randomised independently for each subject and each session and computer controlled, with stimuli removed for being assumed to be too high or low in magnitude based on the subjects' response.

A subset of ten males from the first experiment participated in the second experiment conducted to determine the effect of vibration frequency in each of the translational directions. Using the same method as the first experiment, subjects were required to respond to test motions compared with a 0.5 ms^{-2} r.m.s. 2 Hz vertical motion, lasting 41 seconds. Subjects responded with a choice of three buttons as stated in the previous experiment. 'Test' motions consisted of digitally filtered Gaussian random vertical vibration centred on 0.5, 1.0, 2.0 and 4.0 Hz and magnitudes 0.1 to 1.0 ms^{-2} r.m.s.

From the second experiment it was concluded that the shape of the contours obtained using sinusoidal and random motion were similar.

Twenty male participants took part in the third experiment focussing on the effect of frequency on lateral vibration discomfort. The method of constant stimuli was employed in this experiment and the order of presentation was 'reference' - 'test' - 'reference' - 'test'. Vibration was produced at a different facility, participants sat on the same seat as the first experiment and similarly their feet moved with the seat. Vibrations were produced at the preferred eleven one-third octave centre frequencies from 0.5 to 5 Hz, with both reference and test stimuli lasting 10 seconds. Comfort contours equivalent to 0.75 ms^{-2} 2 Hz lateral vibration were obtained for motions in the lateral axis across. The equivalent level at each frequency was determined from the geometric mean of the highest level of the test motion considered less uncomfortable than the reference, and the lowest level considered more uncomfortable than the reference.

Subjects had no control over the magnitude or duration of the signal and answered by circling their response on a sheet of paper provided and also communicated their response to the experimenter. Due to the lack of a computer, the stimuli were provided using pre-recorded sequences of motion recorded on an FM tape recorder. The order of the presentation of stimuli was randomised into four sequences and each participant was randomly assigned into one of four groups, each receiving a different order of 'test' stimuli.

2.6.3.6 **Measurement**

Following on from the four-part series from 1982, the current British standard (BSI 6841:1987) was produced and defines procedures to predict vibration discomfort based on measurement, evaluation, and assessment. There are some small differences between the British and International standards, such as the use of W_b for weighting seated vertical vibrations in the British standard as opposed to W_k used in the International standard, the following will be based on BS:6841:1987 but is similar to ISO 2631-1:1997 (see Section 2.6.3.9 for differences).

The first step of predicting vibration discomfort in a transport environment is the measurement of vibration. The data processing techniques are also applicable to computer simulations and the locations and axes of vibration taken in the simulation should reflect those suggested for measurements.

The unit used for expressing vibration magnitude is the weighted root-mean-square (r.m.s.) acceleration in ms^{-2} for translational vibration and rad s^{-2} for rotational vibration. The direction of the measurement should be in accordance with the coordinate system shown in Figure 2.13. It is noted in part 3.2 that the measurement axes may deviate by up to 20 degrees from the ideal basicentric axes where seats are inclined.

There is some flexibility of the locations of rigid supporting surfaces allowing for transducers to be placed up to 100 mm from the centre of the supporting surface. For non-rigid surfaces, the transducers must be placed between the person and the 'principal contact areas of the surface'. This is somewhat ambiguous as it allows for transducers to be tactically placed especially at the back, where if there is a significant amount of roll or pitch motion, the resulting lateral or fore-and-aft motion at the backrest will be greater with increasing distance from the centre of rotation. Guidance is given in 'NOTE 2' to place the transducer underneath the ischial tuberosities at the seat surface but remains ambiguous for the backrest, offering "measurements on the seat-back should be made at the position with the greatest effective vibration contact with the body".

2.6.3.7 **Evaluation**

As described above, unprocessed vibration time histories may offer little insight into the vibration discomfort experienced by a human passenger. Knowledge of the frequency-dependence of vibration discomfort can be used to evaluate measured data to reflect better human sensitivity to vibration. From the knowledge obtained from many previous laboratory and field experiments including the four-part series on vibration and comfort, frequency weightings have been developed based upon the frequency-dependence of vibration discomfort at each location (seat, backrest, feet), and axis (fore-and-aft, lateral, vertical, roll, pitch, yaw) of vibration. Figure 2.17 shows the realisable frequency weightings for seated passengers found in BS 6841 (1987).

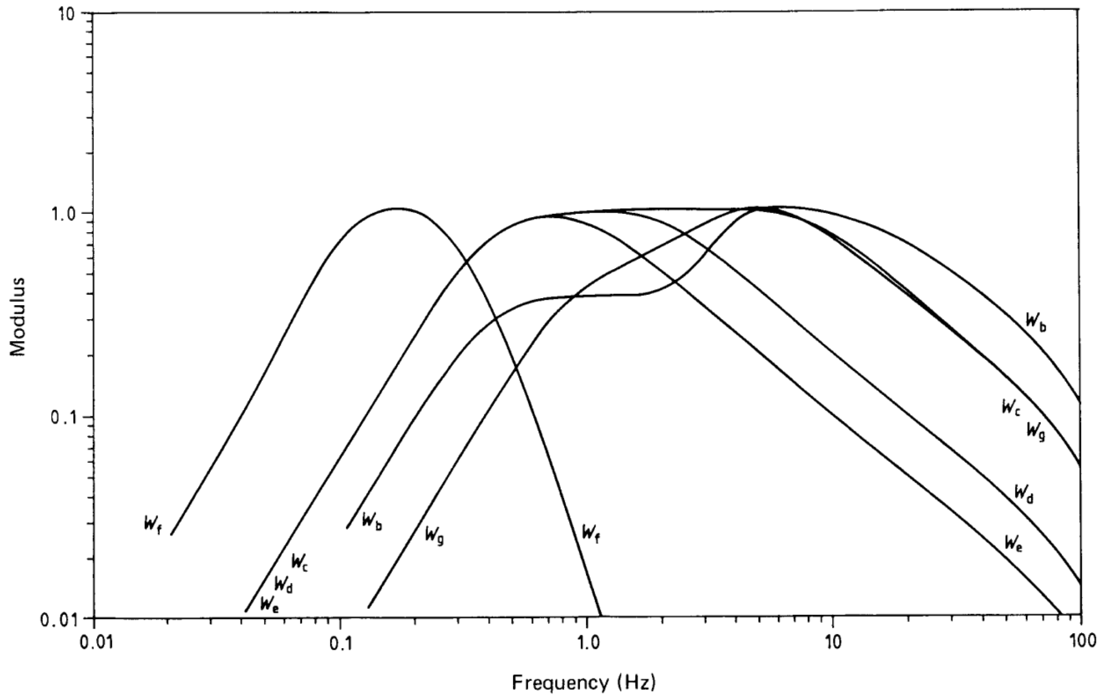

Figure 2 — Moduli of the frequency weightings with band-limiting filters

Figure 2.17 Realisable frequency weighting curves for seated passengers from Figure 2 in BSI 6841 (1987).

The British standard allows the use of r.m.s. of the frequency weighted accelerations for reporting vibration magnitude for evaluating discomfort at each input location and axis:

$$rms = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \tag{2.16}$$

There is however a time averaging component of the r.m.s. method that has been shown to underestimate discomfort from occasional shocks (Griffin and Whitham, 1980a). For vibration containing occasional shocks or intermittent vibration with high crest factors (described as the ratio between the maximum peak in a time history and the r.m.s. value) above 6.0 (or 9.0 in ISO 2631-1:1997) the root-mean-quad (r.m.q.) method is recommended over the r.m.s:

$$rmq = \left[\frac{1}{T}\int_0^T a_w^4(t)dt\right]^{\frac{1}{4}} \tag{2.17}$$

A minimum measurement duration (*T*) of 60 seconds is required for the r.m.q. method.

By removing the time averaging component from equation (2.16), the vibration dose value (VDV) is able to give comparisons of vibration exposures of different durations:

$$VDV = \left[\int_0^T a_w^4(t)dt\right]^{\frac{1}{4}} \tag{2.18}$$

Relative discomfort between directions and locations of vibration (see section 2.4.3) are taken into account with the use of multiplying factors to reduce unnecessary repetition of identical frequency weightings at different magnitudes. Table 2.3 shows the multiplying factor for each of the twelve axes of seated human vibration as determined by research on the relative sensitivity of each input.

Table 2.3 Axis multiplying factors for the evaluation of seated passenger discomfort (BSI 6841:1987).

Axis	Multiplying factor
Seat Surface	
Fore-and-aft	1
Lateral	1
Vertical	1
Roll	0.63
Pitch	0.4
Yaw	0.2
Backrest	
Fore-and-aft	0.8
Lateral	0.5
Yaw	0.4
Feet	
Fore-and-aft	0.25
Lateral	0.25
Yaw	0.4

The British standard (6841:1987) requires the reporting of the true r.m.s. value determined for each frequency-weighted acceleration signal in every axis. However, it may be practical to use a reduced number of vibration discomfort values or a single vibration discomfort value to compare multiple rides, especially where the dominant axis of vibration discomfort is different. For the combination of axes within a location, and the combination of locations within a single ride, the root-sums-of-squares is recommended:

$$a = \left(k_x {a_{xw}}^2 + k_y {a_{yw}}^2 + k_z {a_{zw}}^2\right)^{\frac{1}{2}} \tag{2.19}$$

where *k* is the multiplying factor taken from table 2.3 for each axis of vibration. There is evidence that the r.s.s. technique is a better prediction method than either linear sum or worst component (see section 2.5.4) and is therefore the preferred method.

It is recommended that where vibration enters the body at more than one point that the r.s.s. is calculated from each axis of each location separately and compared separately with specifications and limits of similar vibration environments. An allowance is made for a single 'overall' ride value calculated from the r.s.s. of each location value.

2.6.3.8 **Assessment**

The assessment of vibration discomfort will usually determine whether the level of discomfort is suitable for a vehicle. Whilst '*an assessment does not necessarily require measurement and evaluation of vibration: a particular type or source of vibration exposure could be labelled as unacceptable without knowledge of vibration magnitudes'* (Griffin, 2007), these steps when taken introduce repeatability into the assessment stage.

Appendix C in British standard 6841:1987 has some useful suggestions about what the measurement and evaluation procedures achieve as well as some general guidance of possible reactions for a range of vibration magnitudes, shown in Table 2.4. The standard suggests that the two principal purposes of frequency-weighted magnitudes are:

a) The provision of a defined objective method of comparing the discomfort due to vibration in different situations; and

b) The provision of a unit which may be used to set specifications for particular systems.

The environment and experience of users will often influence the acceptability of a vibration level, however as a general guide Table 2.4 can be useful to indicate general reactions to ranges of frequency weighted vibration magnitude

Table 2.4 Approximate indications of the likely reactions to various magnitudes of frequency weighted r.m.s. acceleration (BS 6841:1987, ISO 2631-1:1997).

Frequency weighted r.m.s. magnitude	Likely reaction
< 0.315 ms^{-2}	Not uncomfortable
0.315 – 0.63 ms^{-2}	A little uncomfortable
0.5 – 1.0 ms^{-2}	Fairly uncomfortable
0.8 – 1.6 ms^{-2}	Uncomfortable
1.25 – 2.5 ms^{-2}	Very uncomfortable
< 2.0 ms^{-2}	Extremely uncomfortable

2.6.3.9 **Key differences between BS 6841:1987 and ISO 2631-1:1997**

The above stages of measurement, evaluation, and assessment were based upon recommendations given in BS 6841:1987 with the assumption that they are similar and relevant to ISO 2631-1:1997, however differences exist, especially in the evaluation, between the two standards.

One of the most important differences between the Standards is the recommendation of the frequency weighting W_k in the International Standard as opposed to W_b in the British Standard. Despite the two weightings being similar, there is no experimental evidence to support the use of W_k over W_b. Furthermore, W_k '*appears to be a less satisfactory predictor of discomfort*' (Griffin, 2007).

There is a clear distinction in the way that crest factors are treated between the British and International standards. The British standard 6841:1987 states that the r.m.s. measures of acceleration may be used when crest factors do not exceed 6.0 and that the preferred method of vibration evaluation is the VDV, which is capable of incorporating motions with high crest factors into the measurement. International Standard 2631-1:1997 suggests that the r.m.s. measure is normally sufficient where crest factors are below 9.0, although also states that the crest factor is an uncertain method of deciding whether the r.m.s. acceleration can be used to assess human response to vibration. In addition, it states that for vibration with occasional peaks, the r.m.s. measure may underestimate discomfort even when the crest factor is below 9.0.

The International Standard 2631-1:1997 allows the use of the maximum transient vibration value (MTVV) or VDV in environments where there are high crest factors, occasional shocks or transient motion. The MTVV produces a value of the worst 1-s period of a frequency-weighted acceleration time history and is therefore only influenced by 1-s of the entire journey. Unlike cumulative methods like the VDV, the MTVV does not combine shocks and vibration or increase in value with increasing duration of measurement, shown to influence ride comfort. Therefore, the MTVV could be considered as a poor indicator of ride quality.

British Standard 6841:1987 uses similar methods for assessing vibration for both comfort and health, with the health evaluation consisting of the same weighting-factors and directional multipliers, although for health evaluation only the three translational directions on the seat surface and fore-and-aft at the backrest are used. International Standard 2631-1:1997 uses the same frequency-weightings with both comfort and health, however when evaluating for health it requires a 1.4 axis multiplier for fore-and-aft and lateral seat surface accelerations and does not require the backrest to be measured, despite potentially being a primary source of vibration. In addition for health evaluation, once each axis is evaluated independently, the assessment of the vibration is made only with respect to the highest frequency-weighted acceleration determined in any axis on the seat pan.

2.7 Remaining challenges to current metrics

2.7.1 Introduction

Since the latest publication of the standards (1987 for BS 6841 and 1997 for ISO 2631-1), research has continued to progress understanding of subjective human responses to vibration. New findings challenge some of the details in the current standards and introduce ideas about the complexity of discomfort and the application of frequency weightings and axis summing methods within the current standards. In addition, where some compromises may have been made to allow the easier adoption of the standards at the time of publishing, signal processing complexity and power have since increased so much so that this should no longer be a limiting factor. With this in mind, three areas of investigation have been identified.

2.7.2 Translational fore-and-aft motion of the backrest due to pitch

Translational fore-and-aft motion of the backrest has been identified as a possible principal source of vibration discomfort. Due to pitch oscillation of a vehicle, fore-and-aft vibration of the backrest may be greater than the fore-and-aft vibration of the seat surface or the floor.

Comparisons between discomfort caused by pitch oscillation on seats with and without backrests have been performed by Wyllie and Griffin (2009) in the frequency range from 0.2 Hz to 1.6 Hz, with discomfort increasing with the presence of a backrest at frequencies above about 0.63 Hz. The W_c weighting given to fore-and-aft backrest vibration suggests greatest sensitivity to acceleration at frequencies up to 8 Hz. A question remaining is: how does a backrest affect the rate-of-growth of vibration discomfort and equivalent comfort contours for pitch oscillation of seated persons in the frequency range 0.5 to 5 Hz?

2.7.3 Magnitude-dependence of the frequency-dependence of vibration discomfort

Briefly discussed in Section 2.3.5, it has been demonstrated that the frequency-dependence of vibration discomfort is dependent on the magnitude of vibration. Both British and International standards assume the same increase in vibration discomfort with vibration magnitude across the entire frequency spectrum at each location of vibration input to a seated persons and in each axis. Referring back to Stevens' Power Law (equation 2.3), this would suggest that the rate-of-growth of discomfort, n, would be the same across all frequencies and all axes. If the mechanism of discomfort is different for different types of vibration discomfort (e.g., shearing forces at the ischial tuberosities, pitching of the torso, resonances of internal organs, pitching of the head/neck etc.) then it is not unreasonable for the rate-of-growth of discomfort to be different for different axes, locations, and frequencies of vibration.

Morioka and Griffin (2006) demonstrated a clear and significant magnitude-dependence of the frequency-dependence of human response to whole-body vibration in the fore-and-aft and vertical directions for seat vibration over the frequency range of 2.0 to 315 Hz for subjects with stationary feet. The W_d frequency weighting given in the standards suggest great importance to horizontal acceleration around 1 Hz, and in many transport scenarios the feet may be moving in unison with the seat surface. In addition, the inter-axis equivalence at low magnitudes between fore-and-aft, lateral, and vertical motion has not been explored in the published papers. How does the magnitude-dependence of the frequency-dependence of vibration discomfort affect the inter-axis equivalence of discomfort for the vibration of seated persons in the fore-and-aft, lateral, and vertical axes over the frequency range of 1.0 to 10 Hz?

2.7.4 Combining directions of motions

The human response to non-sinusoidal dual-axis vibration and tri-axial vibration of seated subjects evaluated using a subjective method (i.e., magnitude estimation) is currently unknown. The rate-of-growth of discomfort is not accounted for in previous objective measurements of multi-axis vibration discomfort (i.e., Griffin and Whitham, 1977; Fairley and Griffin, 1988; Mistrot *et al.,* 1990). Using objective measurements, the value obtained for the power summation method (i.e., 2 in r.s.s.) of combining discomfort from multiple axes may differ from that obtained using subjective methods.

Additionally, the difference in discomfort of complex combined motions in comparison to the individual component motions may not be similar to that of sinusoidal motions due to the unpredictability of random motions.

When using a power summation method to predict discomfort caused by octave-bandwidths of random multi-axis vibration, what power is appropriate, and does the rate of growth of discomfort affect the optimum value used in the power summation?

Chapter 3 Methods

3.1 Introduction

This chapter describes the equipment and analysis methods employed in the studies. Further information relating to the equipment, setup, and analysis of data specific to each experiment can be found in the appropriate chapters of this thesis.

3.2 Apparatus

3.2.1 6-axis motion simulator

A hydraulic simulator capable of reproducing multi-axis motions in three translational directions: fore-and-aft, lateral, and vertical and three rotational directions: roll, pitch, and yaw was used in all four experiments (Figure 3.1). The maximum peak-to-peak displacement is 500 mm in the fore-and-aft and lateral directions, 1000 mm in the vertical direction and 20 degrees in the rotational axes. The frequency range of the simulator is 0 to 50 Hz and can achieve up to 10 ms^{-2} translational and 5 $rads^{-2}$ peak acceleration.

Figure 3.1 6-axis motion simulator.

The 6-axis motion simulator was controlled by a Pulsar Digital Controller provided by Servotest Systems. Motion stimuli were created using MATLAB (version 2015a) software in all 6 axes and used by the Pulsar system to drive the simulator for the required motions. Vibration signals were created at 512 samples per second using *HVLab* (version 1.1) software and low-pass filtered at 50 Hz.

3.2.2 Transducers and signal conditioning

Motion stimuli were recorded using Silicon Design 2260-005 piezo-capacitive accelerometers Figure 3.2. Table 3.1 details the specification of the accelerometer.

Where a compliant seat was used (experiment 2) and to check the transmissibility of the beanbag (see section 3.2.3) was unity over the frequency range studied, a SIT-pad was placed on the seat pan and backrest between the body and the seat. Figure 3.3 shows the SIT-pad and its construction and Table 3.2 details the specification of the accelerometers.

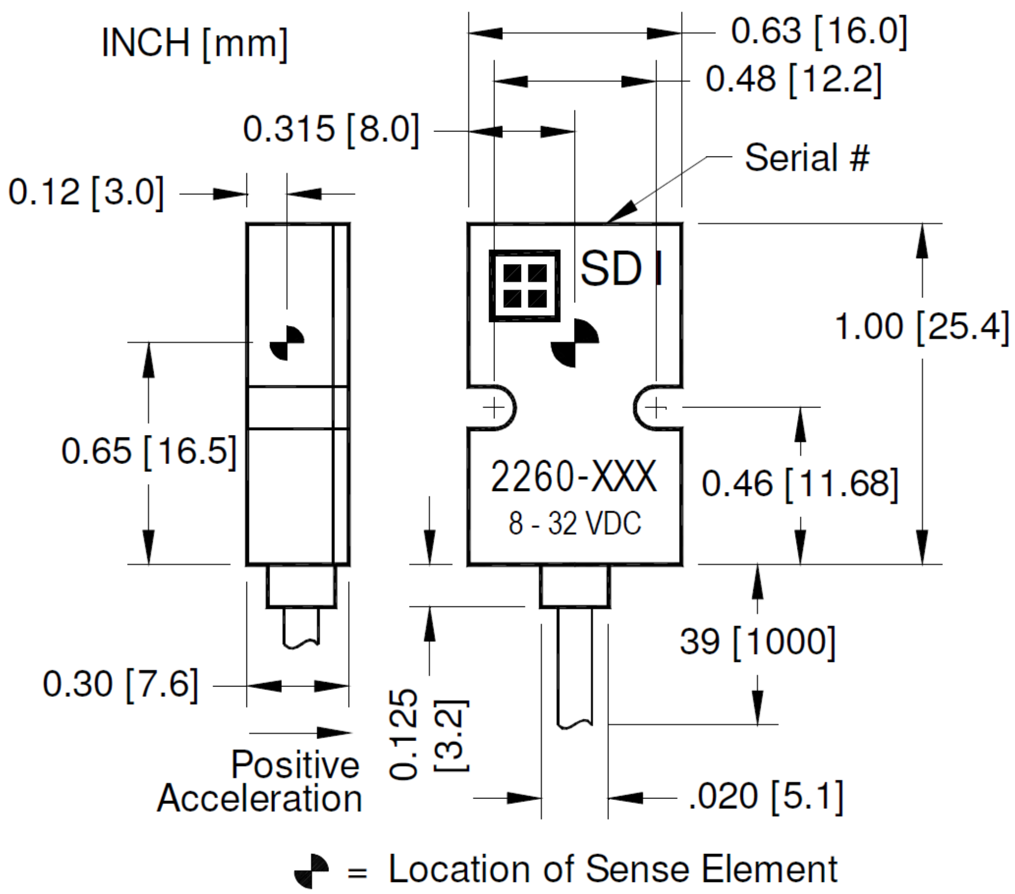

Figure 3.2 Single-axis piezo-capacitive accelerometer Silicon Design 2260-005.

Table 3.1 Specifications of Silicon Design 2260-005

Parameter	Specification
Input range (g)	±5
Frequency response (Hz)	0 – 600
Sensitivity (mV/g)	800
Output noise (µg/(root Hz)	12
Maximum mechanical shock (g)	2000

Data acquisition was carried out using *HVLab* Signal Processing toolbox (version 1.1) in MATLAB (version R2009) using a National Instruments NI 6211 data acquisition card equipped with analogue-to-digital converters. Prior to the NI card, acceleration signals were amplified using FYLDE FE-366-TA dual channel amplifiers. Before and after each acceleration measurement period (typically the entire set of motion stimuli), the transducers were calibrated using a turn-over test and gravity acceleration (±*g*), appropriate as the transducers have a DC response.

3.2.3 Seating

All four experiments involved seated participants and used one of four seating conditions: flat rigid seat with a backrest, flat rigid seat without a backrest, bean bag covered rigid seat without a backrest, and a compliant seat provided by Jaguar Land Rover.

Two rigid seats were used across the experiments. The first used in experiment 1 (Figure 3.4) had a seat-pan height of 0.42 m, width of 0.60 m, depth of 0.45 m and a removable backrest with a height of 0.56 m above the top of the seat-pan. The seat had an aluminium frame and wooden seat-pan and backrest. The angle of the seat-pan was parallel to the floor and the backrest 90 degrees to the seat-pan.

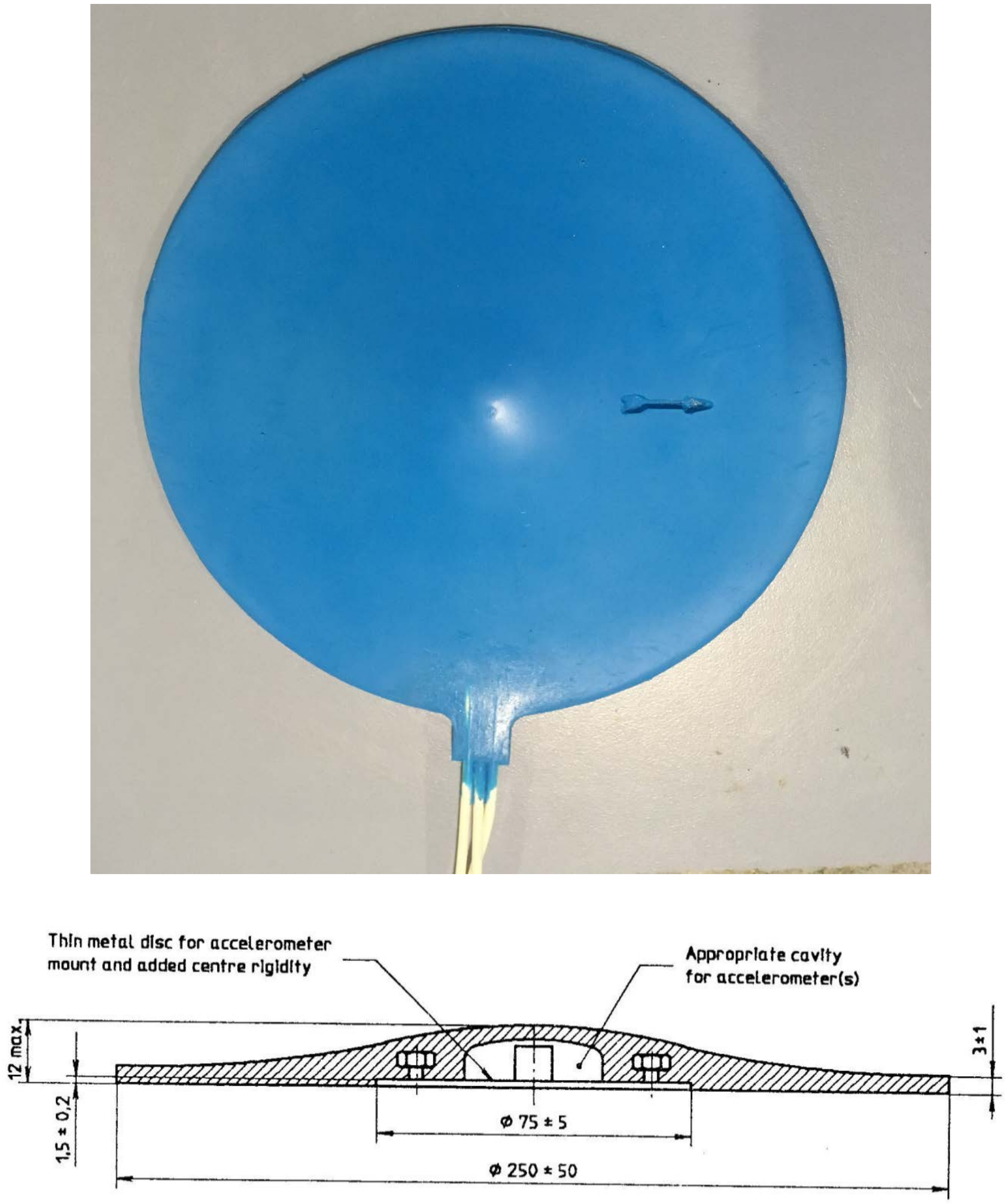

Figure 3.3 SIT-pad and its construction (ISO 10326-1, 1992).

Table 3.2 Specifications of SIT-pad.

Parameter	Specification
Input range (*g*)	± 10
Frequency response (Hz)	0 – 800
Sensitivity (mV/g)	200
Output noise (µ*g*/(root Hz)	100

Figure 3.4 Rigid seat used in experiment 1 with and without the backrest present.

The second rigid seat (Figure 3.5) used in experiments 3 and 4 had a seat-pan height of 0.56 m, width 0.50 m, and depth 0.50 m. The seat had had its backrest removed during the experiments and was constructed from an aluminium frame and a wooden seat-pan. The angle of the seat-pan was parallel to the floor. A 'bean bag' was used for half of experiment 3 and throughout experiment 4. The bean bag had a height of 0.065 m, width 0.41 m, and depth 0.45 m, was filled with small rigid plastic pellets, and had a transmissibility of unity in the three translational directions over the range of frequencies investigated.

A compliant seat was used in experiment 2. The seat had a steel and foam construction and was upholstered in leather. The seat (Figure 3.6) had a seat-pan height of 0.42 m, width of 0.60 m, depth of 0.45 m and backrest with a height of 0.56 m above the top of the seat-pan. The seat-pan was angled at 24 degrees from the floor and the backrest was angled at 92 degrees from the seat-pan. The headrest was removed during experimentation (as pictured).

In all of the above seating conditions, rigid wooden footrests were provided to achieve thigh-contact conditions detailed in each experiment. Footrests parallel to the floor were used in conditions with the rigid seats and rigid seat with bean bag, an angled footrest was used with the compliant seat.

Figure 3.5 Rigid seat used in experiments 3 and 4 with and without the beanbag

Figure 3.6 Compliant seat used in experiment 2.

3.2.4 Vibration measurement

All vibration measurements used the basicentric coordinate system as defined in BS 6841 (1987), shown in figure 3.7.

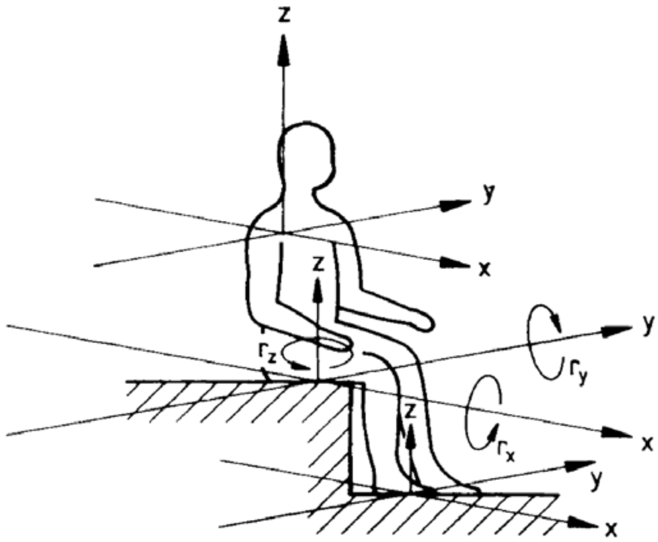

Figure 3.7 Basicentric coordinate system for a seated person defined in BS 6841 (1987).

3.3 Test conditions

3.3.1 Vibration conditions

In all four experiments, participants were exposed to vibration. All experiments were conducted in the Human Factors Research Unit laboratories at the Institute of Sound and Vibration Research, University of Southampton. All experiments were carried out with prior approval from the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton, relevant approval numbers are stated in each experiment Chapter (Chapters 4 – 7). All vibration exposures within a session did not exceed 15 $ms^{-1.75}$ and were classed as 'USUAL' in accordance with ISVR Technical Memorandum 808: Guide to Experimentation involving Human Subjects (Anon, 1996) and British Standard 6841 (1987).

All participants were volunteers and could end the experiment at any time without providing a reason. For each experiment, participants received an instruction sheet via email at least 24 hours prior to the experiment and a copy was available before the experiment started. Copies of these instruction sheets are provided in the appendices.

3.3.2 Visual and acoustic conditions

During all experiments, participants were instructed to keep their eyes closed to avoid visual cues affecting their judgement of vibration magnitude.

To mask any external noise from the laboratory, participants wore headphones providing white noise at 65 dB (A) during experiments. The white noise system was calibrated using the same headphones worn during the experiment.

In all experiments, the experimenter communicated with participants with a microphone connected to the headphones.

3.4 Psychophysical methods

3.4.1 Magnitude estimation

In experiments 1, 3, and 4, the method of magnitude estimation was used (see section 2.2). Participants were given training in the method consisting of judging lengths of lines on a sheet of paper and with a short practice using vibration stimuli in the same conditions as the full experiment. After the training, a reference stimulus was provided to each participant and they were instructed that this represented a discomfort level of '100'. The reference stimulus was in the centre of the frequency and magnitude range as suggested by Stevens (1975). The reference level was not repeated again for the entire experiment.

3.4.2 Stevens' Power law

In experiments 1 and 3, Stevens' power law (Stevens, 1975) was used to relate the physical magnitude, φ, of a motion to the magnitude of the sensation experienced, ψ:

$$\psi = k\varphi^n \tag{3.1}$$

where *k* is a constant and denotes the units of the physical stimulus and *n* is the rate-of-growth of sensation, in this case the rate of growth of discomfort with increasing vibration magnitude. The logarithmic transformation of Equation 3.1 can be expressed as:

$$\log_{10}(\psi) = n\log_{10}(\varphi) + \log_{10}(k) \tag{3.2}$$

This transformation allows for linear regression to be performed between the experimental values of ψ and φ to calculate magnitude estimates of *n* and *k*. Values of *n* and *k* were calculated for each participant rather than across the data set to represent the sensitivity of each subject individually and allowed for greater statistical testing of the parameters.

Equivalent comfort contours can be determined from values of *n* and *k* using equation 3.3:

$$\varphi = \left(\frac{\psi}{k}\right)^{1/n} \tag{3.3}$$

Equivalent comfort contours were determined at various magnitudes for both experiments 1 and 3 for each individual for statistical testing, and the median comfort contours are shown in this thesis.

When magnitudes are close to thresholds of perception, an additional term is necessary as discussed in section 2.2 and can be seen in Equation 3.4:

$$\psi = k(\varphi - \varphi_0)^n \tag{3.4}$$

However, as the magnitudes used were not close to perception thresholds and there was no evidence of a curvilinear regression in the individual data as seen by Morioka and Griffin (2006a), this additional term was not used.

3.4.3 Method of paired comparisons

In experiment 2, the method of paired comparisons was used. This method involves detecting differences among samples by the relative judgement between pairs of samples. Scheffe's method of paired comparisons was chosen (Miura *et al*, 1973) as described by Ebe (1998), it can provide detailed information about the samples and investigate the primary effect, combination effect, and the order effect.

3.4.3.1 Analysis of variance

The following equations are methods to obtain the primary effect, combination effect, the order effect, the total sum of squares and the error for analysis of variance (Miura *et al*., 1973; as described by Ebe, 1998).

The sums of squares for the primary effect (S_α) and its degrees of freedom (f_α) are calculated from equations 3.5 and 3.6:

$$S_\alpha = \Sigma(x_{i..} - x_{.j.})^2 / (2tp) \tag{3.5}$$

$$f_\alpha = t - 1 \tag{3.6}$$

where x is the assigned category number (preference scale), the first subscript is the first condition of the pair, the second subscript is the second condition and the third is the participant, t is the number of sample and p is the number of participants.

The combination effect ($S_γ$) and its degrees of freedom ($f_γ$) are calculated from equations 3.7 and 3.8:

$$S_γ = Σ_jΣ_i<j\ (x_{ij.} – x_{ji.})^2 / (2p) – S_α \qquad (3.7)$$

$$f_γ = {}_tC_2 – (t\text{-}1) \qquad (3.8)$$

The order effect ($S_δ$) and its degrees of freedom ($f_δ$) are calculated by equations 3.9 and 3.10:

$$S_δ = Σ_jΣ_{i<j}\ (x_{ij}. + x_{ji}.)^2 / (2p) \qquad (3.9)$$

$$f_δ = {}_tC_2 \qquad (3.10)$$

The total sums-of-squares (S_T) and and its degrees of freedom (f_T) are calculated from equations 3.11 and 3.12:

$$S_T = Σ_iΣ_jΣ_lx_{ijl}^2 \qquad (3.11)$$

$$f_T = 2p \text{ x } {}_tC_2 \qquad (3.12)$$

The sums-of-squares for error (S_e) and its degrees of freedom (f_e) are calculated from equations 3.13 and 3.14:

$$S_e = S_t – Σx_{ij}^2 / p \qquad (3.13)$$

$$f_e = 2(p\text{-}1) \text{ x } {}_tC_2 \qquad (3.14)$$

The average scale for the popularity, in this thesis referred to as a comfort score, from the subjects (αi) is calculated from equation 3.15:

$$α_i = (x_{i..} – x_{.i.}) / 2tp \qquad (3.15)$$

With regard to the difference between comfort scores of different conditions, the amount of difference corresponding to a different probability or significance level ($Φ$) is calculated by a 'yardstick' ($Y_Φ$):

$$Y_Φ = q_Φ\ (t,f_e) \text{ x } ((σ^2 / 2pt))^{½} \qquad (3.16)$$

where $q_Φ$ is the student's range (Miura *et al.*, 1973), and $σ^2$ is the variance of the error.

3.4.4 Power summation method

In experiment 4, the method of power summation was used as the strategy for the summation of multiple-frequency components of vibration within an axis as well as multiple-axis components. Proposed by Fothergill and Griffin (1977) as a method for combining the discomfort of multiple frequency motions in a single axis and shown to be a reasonable predictor of multi-frequency vibration discomfort. Additionally used and shown to be a reasonable predictor of multi-axis vibration by Griffin and Whitham (1977), Fairley and Griffin (1988), Mistrot *et al* (1990), and Thuong and Griffin (2015). An example of the power summation equation is given as:

$$\psi_{total} = (\psi_a^{\alpha} + \psi_b^{\alpha})^{1/\alpha} \tag{3.17}$$

where ψ_{total} is the magnitude estimate from a combined frequency or combined axis motion, and ψ_i is the magnitude estimate of a single component of the motion (single frequency, single axis), two components are shown in equation 3.17 although this can be extended indefinitely.

3.5 Objective measurements

Experiment 2 involves a multi-axis complex motion for subjects on a non-rigid seat. For comparison with the results from the subjective results, component and total ride comfort evaluation was performed in accordance with BS 6841 (1987), with total ride comfort values calculated using the r.s.s. method. Table 3.3 details the frequency weightings and axis multiplying factors used for discomfort evaluation, Figure 3.8 shows the moduli of the frequency weightings found in BS 6841(1987).

Acceleration measurements were recorded in the translational directions on the floor using Silicon Design accelerometers, with four vertical inputs at each corner of the seat rail used to calculate roll and pitch, and two fore-and-aft inputs at the left and right front corners of the seat rail to calculate yaw on the floor. Acceleration measurements were recorded on the seat surface and backrest surface using SIT-pads, under the ischial tuberosities on the seat surface and at the principal contact location between the back and backrest surface on the backrest.

Table 3.3 Frequency weightings and axis multiplying factors used for the evaluation of discomfort of seated persons (BS 6841:1987).

Input location	Frequency weighting	Axis multiplying factor
Seat – *x*	W_d	1.0
Seat – *y*	W_d	1.0
Seat – *z*	W_b	1.0
Seat – *roll*	W_e	0.63
Seat – *pitch*	W_e	0.4
Seat – *yaw*	W_e	0.2
Backrest – *x*	W_c	0.8
Backrest – *y*	W_d	0.5
Backrest – *z*	W_d	0.4
Feet – *x*	W_b	0.25
Feet – *y*	W_b	0.25
Feet – *z*	W_b	0.4

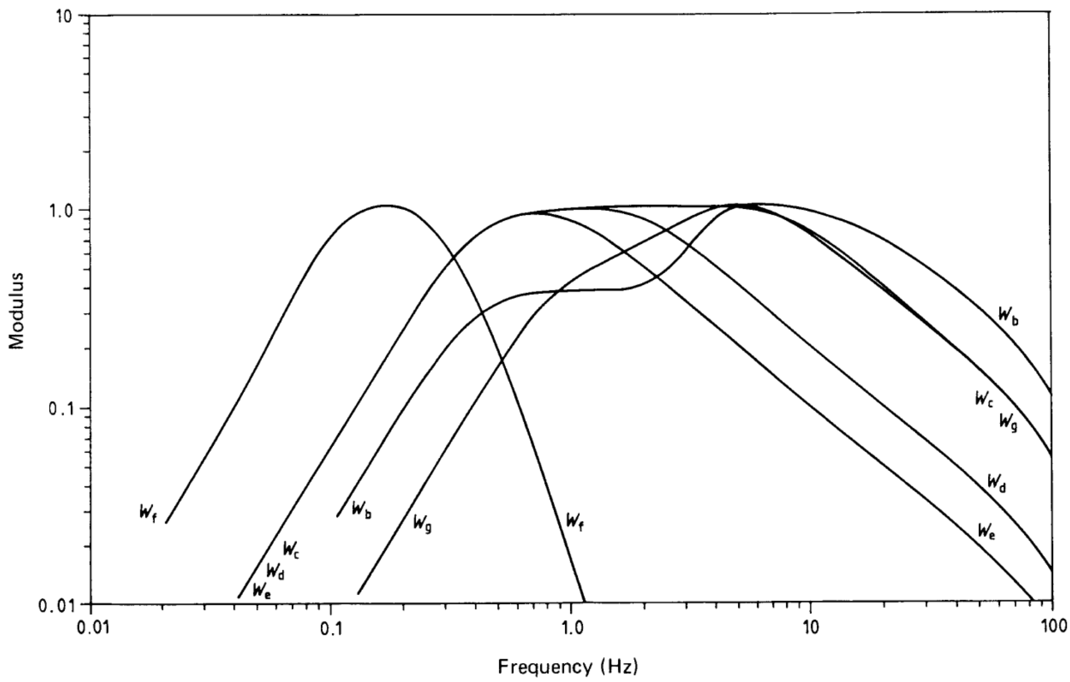

Figure 3.8 Moduli of frequency weighting curves for seated passengers (BSI 6841:1987).

3.6 Data analysis

3.6.1 Data analysis software

Data acquisition and signal processing was performed by the *HVLab* Human Response to Vibration Toolbox for MATLAB Signal Processing Toolbox (version 1.0). Excel was used to perform linear regressions and to derive equivalent comfort contours. IBM SPSS Statistics (version 22) was used to perform all statistical tests.

3.6.2 Statistical tests

No assumption was made over the distribution of data leading to the use of non-parametric statistical tests in experiments 1, 3, and 4. Table 3.4 shows the tests used in this thesis.

Table 3.4 Non-parametric statistical tests used in this thesis.

Statistical test	Category	Type of data
Friedman two-way analysis of variance test	*k* related samples	Continuous
Wilcoxon matched pairs signed-ranks test	2 related samples	Continuous
Kruskal-Wallis one-way analysis of variance	*k* independent samples	Continuous
Wilcoxon Mann-Whitney-U test	2 independent samples	Continuous
Spearman rank-order correlation coefficient	Correlation between two variables	Continuous
Cochran Q test	*k* related samples	Dichotomous
McNemar change test	2 related samples	Dichotomous

Chapter 4 Effect of a backrest on the discomfort caused by pitch oscillation in the frequency range 0.5 to 5.0 Hz

4.1 Introduction

The discomfort experienced by vehicle drivers and passengers depends on the frequency, the magnitude, the direction, and the duration of the vibration. British Standard 6841:1987 and International Standard 2631-1:1997 define frequency weightings and multiplying factors for predicting the discomfort caused by different directions of vibration at different input locations to the body. These weightings were mainly derived from laboratory studies of the discomfort caused by sinusoidal vibration (Griffin, 2007).

A previous study has shown that pitch oscillation of a vehicle can be a principal cause of the fore-and-aft vibration at a backrest (Qiu and Griffin, 2005). Understanding the role of pitch oscillation is therefore important when measuring the ride in a vehicle and when predicting and optimising vehicle vibration.

In one of a four-part series of studies, Parsons and Griffin (1982) determined equivalent comfort contours for rotational whole-body vibration (i.e., roll, pitch and yaw oscillation) over the frequency range of 1 to 31.5 Hz relative to the discomfort caused by vertical whole-body vibration. The final paper in the series presented median equivalent comfort contours for all twelve axes by fitting lines of constant acceleration or constant velocity to the experimental data, so as to create simplistic frequency weightings (Griffin *et al*., 1982b). For pitch vibration at the seat, the experimentally derived equivalent comfort contour was approximated by a slope of constant velocity over the frequency range 1 to 31.5 Hz, although this slightly underestimated discomfort at frequencies greater than 10 Hz. The fitted slope was used to form the W_e weighting in BS 6841:1987 and, subsequently, ISO 2631-1:1997.

At the time when the standards were produced, the facilities for investigating the discomfort caused by pitch oscillation were very limited. The experimental studies were restricted to the frequency range 1 to 31.5 Hz and conducted with pitch oscillation of a rigid flat seat with no backrest and with the feet resting on a stationary support. With low frequencies of pitch oscillation of the seat, relative motion between the front of the seat and the stationary feet may have contributed to discomfort around the thighs that will not be present if the seat and feet move together, as in most transport environments (Jang and Griffin, 2000).

Rotational vibration produces translational oscillation at points away from the centre of rotation. Pitch oscillation of a floor supporting a seat causes fore-and-aft motion at the seat backrest, with the magnitude of fore-and-aft vibration increasing up the height of the backrest. Parsons and Griffin (1978) investigated the effect of the position of the axis of rotation on discomfort caused by whole-body roll and pitch vibrations of seated persons. It was suggested that if subjects sat away from the centre-of-rotation, translational motion from the rotation can be experienced. It was discovered that at frequencies and directions where subjects would be expected to be more sensitive to translational motion than rotational, equivalent comfort contours followed the shape of the translational component as the distance from the centre-of-rotation increased and thus the translational motion due to rotation increased. At frequencies and directions where subjects were not sensitive to the translational component, the increased distance from the centre-of-rotation did not change the shape of the equivalent comfort contour when compared to that experienced on-axis. Parsons and Griffin (1978) concluded that the discomfort when sitting away from the axis of rotation, which comprised of rotational and translational motion, could be adequately predicted by the most severe component (either translational or rotational) of the equivalent comfort contours or the root-sums-of-squares (r.s.s.) of the equivalent levels of both components.

Equivalent comfort contours for fore-and-aft and pitch oscillation over the frequency range 0.2 to 1.6 Hz have been determined with and without a backrest (Wyllie and Griffin, 2009). It was concluded that at frequencies less than about 0.8 Hz, the main contributor to overall discomfort was acceleration in the plane of the seat due to gravity acting through the angle of pitch at the seat (i.e., g sin θ, where θ is the angle of pitch in degrees). At frequencies greater than about 0.8 Hz, the fore-and-aft acceleration of the backrest seemed to be the principal cause of discomfort.

The relationship between the magnitude of a vibration, φ, and the subjective response to the vibration, ψ, can be expressed using Stevens' power law:

$$\psi = k.\varphi^n \quad (4.1)$$

where *n* is the 'rate of growth' of sensation (e.g., discomfort) and *k* is a constant.

During the past decade, it has become recognised that *n*, the rate of growth of sensation with increasing vibration magnitude, varies according to the frequency, direction, and location of input of vibration to the body. This means that the shapes of equivalent comfort contours vary with the magnitude of vibration, and the equivalence between directions of vibration and locations of input of vibration to the body varies with the magnitude of vibration (e.g., Morioka and Griffin, 2006a; Wyllie and Griffin, 2009; Basri and Griffin, 2013). The magnitude-dependence of equivalent comfort contours means that a single frequency weighting, as offered in the standards, cannot provide an optimum prediction of the discomfort caused by a range of vibration magnitudes, frequencies, and directions.

From the studies of Wyllie and Griffin (2009) it seems that the discomfort caused by pitch oscillation at the surface of a seat pan may often be predicted from the root-sums-of squares of the following components, where the frequency weightings W_c, W_d, and W_e are as defined in BS 6841:1987:

- pitch acceleration in the plane of the seat in rad.s^{-2} (using frequency weighting W_e, with a multiplying factor of 0.4),
- fore-and-aft acceleration calculated from the angular displacement, θ, at the seat multiplied by gravity (i.e., g sin θ) (using frequency weighting W_d, with a multiplying factor of 1.0),
- fore-and-aft acceleration at the backrest (if present) calculated from the height of the backrest, h, (in metres) and the pitch acceleration, $\ddot{\theta}$ (in radians) (i.e., $h.\ddot{\theta}$) (using frequency weighting W_c with a multiplying factor of 0.8).

The fore-and-aft acceleration at the feet caused by pitch oscillation at the surface of the seat (either due to the gravitational component, g sin θ, or because the feet are distant from the centre of rotation), is assumed to be negligible due to relatively low sensitivity to vibration of the feet in the fore-and-aft direction (see Wyllie and Griffin, 2009; Morioka and Griffin, 2010a), and so vibration at the feet will be ignored.

Since pitch oscillation can produce several motions that cause discomfort, it is desirable to understand better the role of pitch motion in a procedure for predicting the discomfort caused by multi-axis and multiple-input vibration. This study was designed to determine how the discomfort caused by pitch oscillation depends on the magnitude of pitch oscillation (0.05 to 4.5 rad.s^{-2} r.m.s.), the frequency of oscillation (0.5 to 5 Hz), and seating conditions (with and without a backrest). It was hypothesised that the rate of growth of discomfort would depend on the frequency of oscillation and that a backrest would have no effect on discomfort at frequencies less than about 1 Hz, because the gravitational component (g sin θ) at the seat pan would be the dominant cause of discomfort. At frequencies greater than about 1 Hz, greater discomfort was expected with the backrest, because fore-and-aft acceleration of the backrest would then be the dominant vibration input to the body arising from the pitch oscillation.

4.2 Method

4.2.1 Participants

Fifteen healthy university students and staff (eight male and seven female) participated in this study. The male participants had a median age of 28 years (range 22 to 30 y), stature 1.80 m (range 1.60 to 1.90 m) and weight 91 kg (62 to 125 kg). The female participants had a median age of 27 years (range 22 to 29 y), stature 1.62 m (range 1.57 to 1.69 m) and weight 55 kg (50 to 68 kg). The physical characteristics of each subject are reported in Table 4.3.

The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (application number 14510).

4.2.2 Motions

Motion stimuli for this experiment were generated using MATLAB (version 2012a) and the *HVLab* toolbox (version 2). The sinusoidal stimuli were at the eleven preferred one-third octave centre frequencies from 0.5 to 5 Hz. The stimuli had durations of approximately 11 seconds to allow for at least five full cycles at the lowest frequency. Stimuli were adjusted to n+0.5 cycles of oscillation, where n is an odd number and modulated by a half sine envelope so that each stimulus started and ended with zero displacement, zero velocity, and zero acceleration, an example stimulus is shown in Figure 4.1. Due to the half sine envelope, the ratio between the peak and r.m.s. acceleration for each stimulus was $\left(\sqrt{2}\right)^2$.

Participants received a ‘reference’ motion at the beginning of each condition; the reference motion was a 1.6 Hz oscillation with a magnitude of 0.53 $rad.s^{-2}$ r.m.s.

At each frequency, the ‘test’ stimuli were presented at six magnitudes in steps of 2 dB (Figure 4.2, Tables 4.1 and 4.2). To obtain a similar range of the subjective magnitudes across the frequency range with and without the backrest, the magnitudes at other frequencies were calculated so that they would be expected to produce similar overall discomfort (using the weightings and multiplying factors in BSI 6841:1987 with the addition of the gravitational factor and using the root-sums-of-squares, r.s.s., to combine the components).

Table 4.1 Participant characteristics

Subject	Gender	Age (y)	Height (m)	Weight (kg)
1	M	22	1.60	68
2	F	23	1.69	52
3	F	25	1.57	50
4	M	30	1.69	62
5	M	28	1.71	63
6	M	28	1.81	94.3
7	F	27	1.61	55
8	F	22	1.67	68
9	F	29	1.60	53
10	M	26	1.78	93
11	F	28	1.62	65
12	M	24	1.85	94.5
13	F	29	1.67	55
14	M	29	1.90	89.5
15	M	28	1.88	125

The stimuli consisted of 66 motions with the backrest and 64 motions without the backrest. The greatest magnitudes at the two highest frequencies (4 and 5 Hz) without the backrest were not presented due to the high magnitudes of simulator pitch acceleration required.

4.2.3 Apparatus

Pitch oscillation was produced by a six-axis motion simulator located in the Institute of Sound and Vibration Research at the University of Southampton. Figure 4.3 shows the experimental setup.

A rigid seat with a removable backrest (seat-pan height 0.423 m, seat-pan depth 0.445 m, backrest height above the seat pan 0.558 m) was mounted on the motion simulator. The centre-of-rotation of the simulator was adjusted to be at the upper surface of the seat pan beneath the ischial tuberosities of the seated subjects.

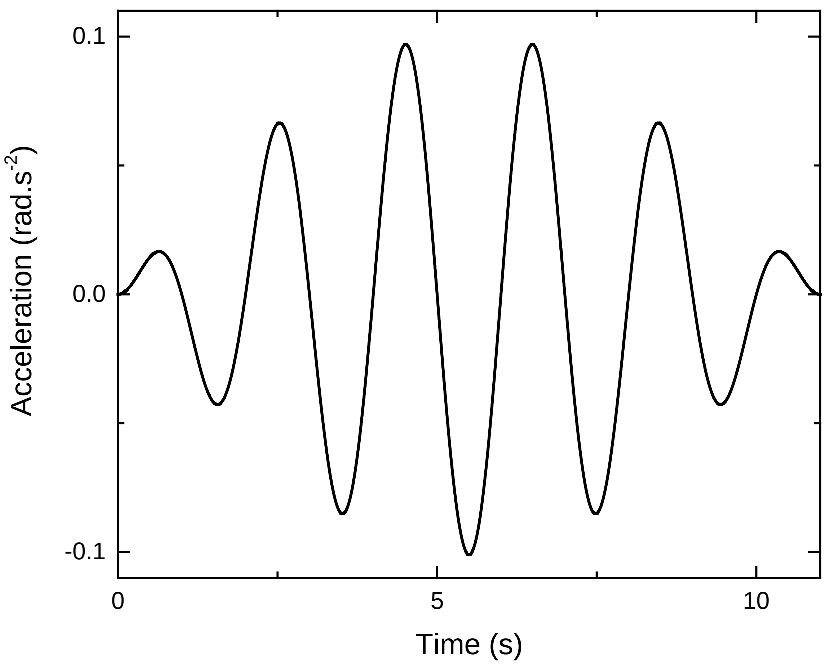

Figure 4.1 Example stimulus with a frequency of 0.5 Hz and magnitude 0.05 rad.s^{-2} r.m.s.

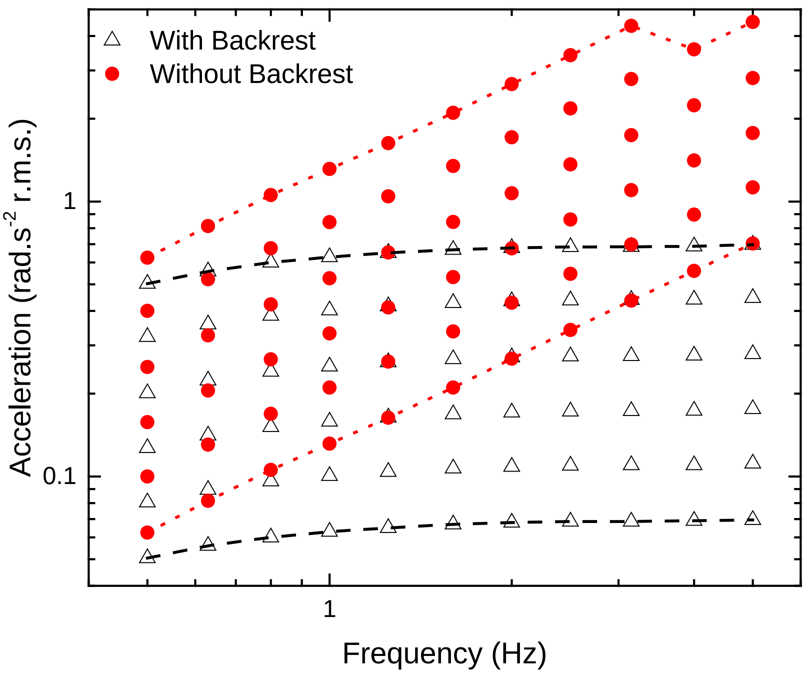

Figure 4.2 Frequencies and magnitudes of oscillation stimuli used in both conditions in the experiment.

Table 4.2 Frequencies and magnitudes of the pitch stimuli in the condition with the backrest.

Frequency (Hz)	Magnitude (rad.s^{-2} r.m.s.)					
0.5	0.05	0.08	0.13	0.20	0.32	0.50
0.63	0.06	0.09	0.14	0.22	0.36	0.56
0.8	0.06	0.10	0.15	0.24	0.38	0.60
1	0.06	0.10	0.16	0.25	0.40	0.63
1.25	0.06	0.10	0.16	0.26	0.42	0.65
1.6	0.07	0.11	0.17	0.27	0.43	0.67
2	0.07	0.11	0.17	0.27	0.43	0.68
2.5	0.07	0.11	0.17	0.27	0.44	0.68
3.15	0.07	0.11	0.17	0.27	0.44	0.68
4	0.07	0.11	0.17	0.28	0.44	0.69
5	0.07	0.11	0.18	0.28	0.45	0.70

Table 4.3 Frequencies and magnitudes of the pitch stimuli in the condition without the backrest.

Frequency (Hz)	Magnitude (rad.s^{-2} r.m.s.)					
0.5	0.06	0.10	0.16	0.25	0.40	0.62
0.63	0.08	0.13	0.21	0.33	0.52	0.81
0.8	0.11	0.17	0.27	0.42	0.68	1.06
1	0.13	0.21	0.33	0.53	0.84	1.31
1.25	0.16	0.26	0.41	0.65	1.04	1.63
1.6	0.21	0.34	0.53	0.84	1.35	2.10
2	0.27	0.43	0.68	1.07	1.71	2.68
2.5	0.34	0.55	0.86	1.36	2.18	3.41
3.15	0.44	0.70	1.10	1.74	2.79	4.36
4	0.56	0.90	1.41	2.24	3.58	-
5	0.70	1.13	1.77	2.81	4.50	-

Figure 4.3 Experimental setup on the 6-axis simulator with backrest (left) and without backrest (right).

4.2.4 Conditions and posture

The participants sat and maintained an upright position on the seat surface, facing forward with their hands on their lap for the duration of the experiment. A footrest was adjusted for each participant so that the upper surfaces of the thighs were horizontal when sitting without motion.

Participants wore a loose lap belt that did not restrict movement or provide support. An emergency stop button was provided for participants that was within easy reach or could be held if necessary.

Participants wore headphones delivering white noise at 65 dB(A) to mask sounds produced by the simulator and closed their eyes during operation to eliminate the visual perception of motion from their evaluations. The experimenter communicated with subjects via a microphone and the headphones.

4.2.5 Procedure

The method of absolute magnitude estimating was employed to determine the discomfort caused by each of the test motions. The participants attended one session of approximately 90 minutes, which included reading instructions, signing a consent form, practice, and participating in the experiment.

Written instructions were given to the participants and they were given practice to demonstrate they understood their task of judging discomfort. The practice of magnitude estimation consisted of judging the lengths of lines drawn on paper followed by judging vibration discomfort when seated without a backrest and exposed to eight motions over the ranges of frequency and magnitude they would experience in the experiment.

In the experiment, an initial reference motion was given to the participants (1.6 Hz, 1 rad.s^{-2} r.m.s.), roughly the centre of the frequency and magnitude range employed in the experiment and it was suggested that this motion be given a value of '100' to make sure participants didn't start the rating too low and run out of values close to zero.

After each test motion, the participants were asked to provide a number reflecting the discomfort caused by the motion. Participants were instructed that the rating should be based on a ratio scale, for example: if a motion caused twice the discomfort of the previous motion then it should be given twice the score, if it caused half the discomfort it should be given half the score etc. and any positive value could be given for discomfort.

Motion stimuli were presented in a random order for each seating condition and the order of the seating conditions was randomised.

4.2.6 Data analysis

The magnitude estimates of vibration discomfort given by each subject over all frequencies and magnitudes and both seating conditions (with and without backrest) were normalised so that the median value was 100 for every subject. The normalisation was performed by calculating the median magnitude estimate over all seating conditions and multiplying each magnitude estimate by the quotient of 100 and the median estimate.

Using Stevens' Power Law, the rate of growth of discomfort, *n,* and the constant, *k*, were determined at each frequency in both seating conditions for every subject by linear regression after logarithmic transformation of Equation 4.1:

$$\log_{10} \psi = n \log_{10} \varphi + \log_{10} k \tag{4.2}$$

where *n* represents the slope (rate of growth of discomfort) and *k* represents the intercept of the linear regression between $\log_{10} \psi$ and $\log_{10} \varphi$. Equivalent comfort contours were then determined from Equation 4.2 by calculating for every individual subject the magnitude of pitch acceleration (i.e., φ in rad.s^{-2} r.m.s., unweighted) required to produce subjective magnitudes, ψ, of 50, 100 and 150 using Equation 4.3:

$$\varphi = \left(\frac{\psi}{k}\right)^{\frac{1}{n}} \tag{4.3}$$

where the acceleration, φ, is determined for the level of discomfort, ψ, at each frequency using the values of *n* and *k* from Equation 4.2.

4.2.7 Statistical tests

The hypotheses were tested using non-parametric statistics in SPSS (version 22). To quantify differences between related samples, the Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks were used. The probabilities shown are not adjusted for multiple comparisons.

4.3 Results

4.3.1 Rate of growth of discomfort

The median values of the rate of growth of discomfort (the exponent, *n*) and the constant (*k*) in Stevens' power law (Equation 4.1) are reported for both conditions in Table 4.4. The median and rate of growth are shown in Figure 4.4 separately for each condition with inter-quartile ranges and together for comparison in Figure 4.5. In both seating conditions the rate of growth of discomfort depended in the frequency of vibration (p=0.002 with backrest, p<0.001 without backrest, Friedman).

With the backrest, the rate of growth of discomfort was less at frequencies from 1.0 to 2.0 Hz than at 3.15 and 4.0 Hz (p<0.05, Wilcoxon) except between 1.0 and 3.15 Hz (p=0.164, Wilcoxon).

Without the backrest, the rate of growth of discomfort tended to decrease with increasing frequency: the rates of growth of discomfort at frequencies less than 1.0 Hz were greater than those at all other frequencies (p<0.05, Wilcoxon) and the rate of growth of discomfort at 5.0 Hz was less than the rate of growth of discomfort at all other frequencies (p<0.05, Wilcoxon).

The backrest increased the rate of growth of discomfort at 1 Hz (p=0.05, Wilcoxon) and at frequencies greater than 2 Hz (p<0.05 at 2 Hz, p<0.01 between 2.5 and 5 Hz; Wilcoxon; Figure 4.5).

Table 4.4 Median values for the constant (*k*) and the exponent (*n*) in Stevens' power law at different frequencies of pitch oscillation, with and without a backrest.

Frequency	Without backrest		With backrest	
(Hz)	*k*	*n*	*k*	*n*
0.5	471	1.03	269	0.90
0.63	324	1.00	249	0.93
0.8	263	0.88	315	1.07
1.0	215	0.77	316	0.89
1.25	180	0.65	226	0.74
1.6	163	0.53	263	0.74
2.0	145	0.63	237	0.78
2.5	163	0.50	297	1.13
3.15	134	0.59	268	0.87
4.0	129	0.43	481	1.17
5.0	179	0.31	322	0.89

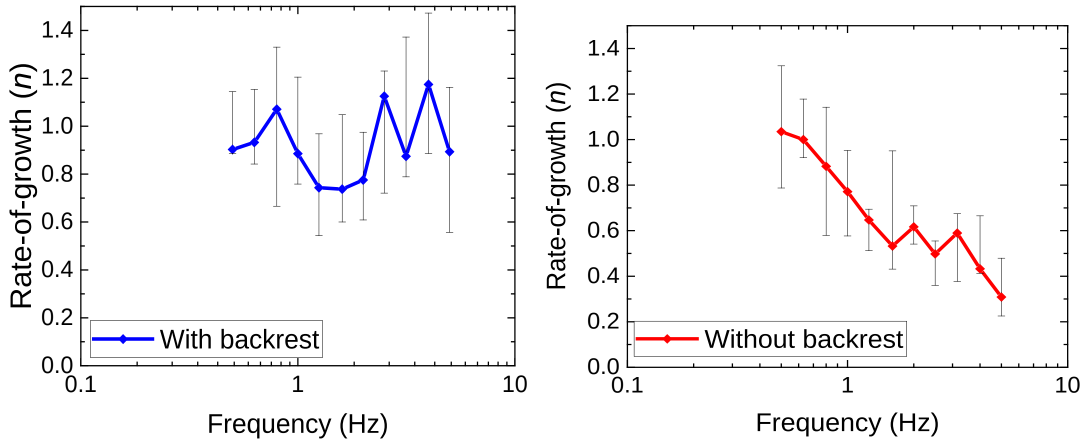

Figure 4.4 Rate-of-growth of discomfort, *n*, for pitch oscillation when sitting with a backrest (left) and sitting without a backrest (right). Median values and inter-quartile ranges from 15 subjects.

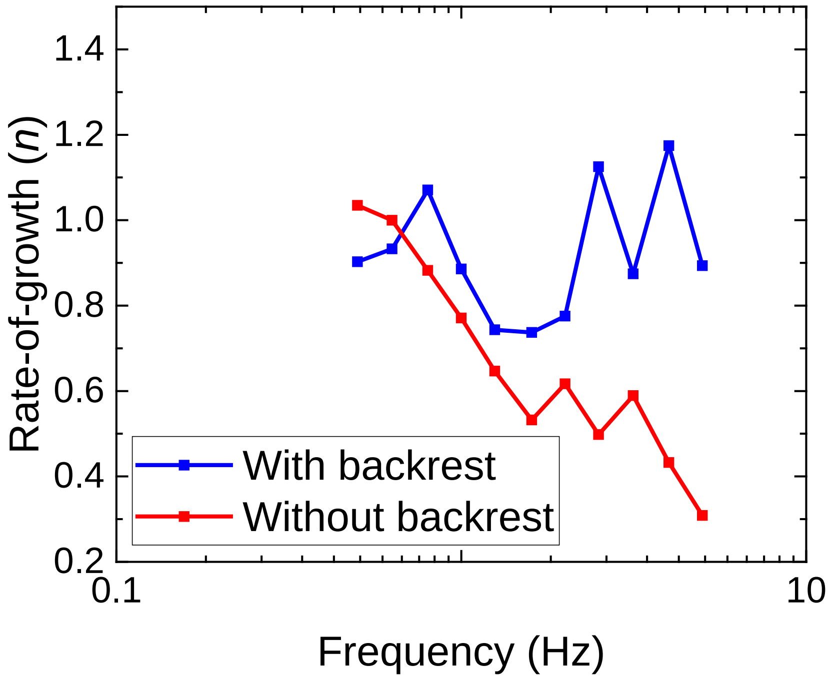

Figure 4.5 Rates-of-growth of discomfort, *n*, for pitch oscillation when sitting with a backrest (blue) and sitting without a backrest (red). Median values and inter-quartile ranges from 15 subjects.

4.3.2 Equivalent comfort contours

Equivalent comfort contours for pitch oscillation when sitting with and without a backrest, constructed using median *n* and *k* values reported above, are shown in Figure 4.6 for subjective values, ψ, of 50, 100 and 150, Figure 4.7 shows a comparison between conditions. As expected from the variation in the rate of growth of discomfort with frequency, the shapes of the contours vary according to the subjective magnitude, with the greatest change in the shapes of the contours when sitting with no backrest.

With a subjective magnitude of 100, the presence of the backrest had no effect on vibration discomfort caused by frequencies less than 1.25 Hz (p>0.1, Wilcoxon), but the backrest increased discomfort at 1.6 Hz (p=0.005; Wilcoxon) and at 3.15 and 4 Hz (p<0.01, Wilcoxon).

When the subjective magnitude increased to ψ = 150, there was still no significant difference between the contours for the two seating conditions at frequencies less than 1.25 Hz (p>0.1, Wilcoxon) but the presence of the backrest increased discomfort at 1.6 Hz (p=0.001, Wilcoxon) and at all frequencies greater than 2 Hz (p<0.02, Wilcoxon) (see Figure 4.7).

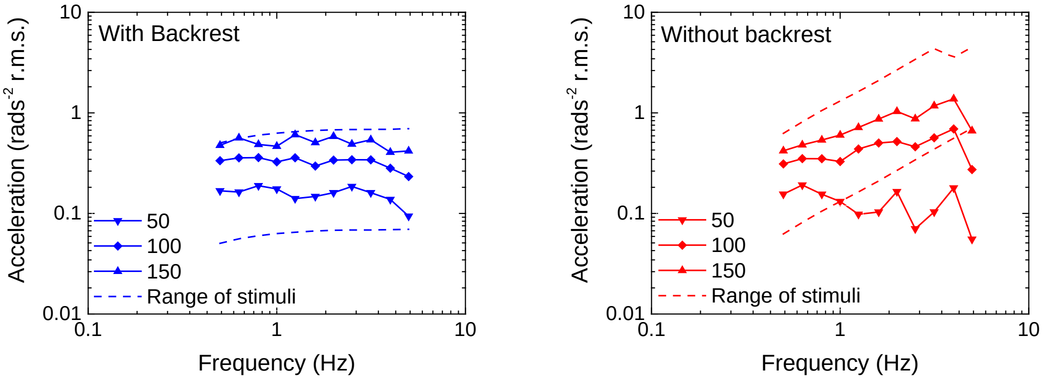

Figure 4.6 Equivalent comfort contours for subjective magnitudes ψ = 50, 100 and 150 in terms of unweighted r.m.s. acceleration calculated from the median equivalent comfort contours of 15 subjects with backrest (left) and without backrest (right). Minimum and maximum magnitudes of vibration employed in the study are represented by (– – –).

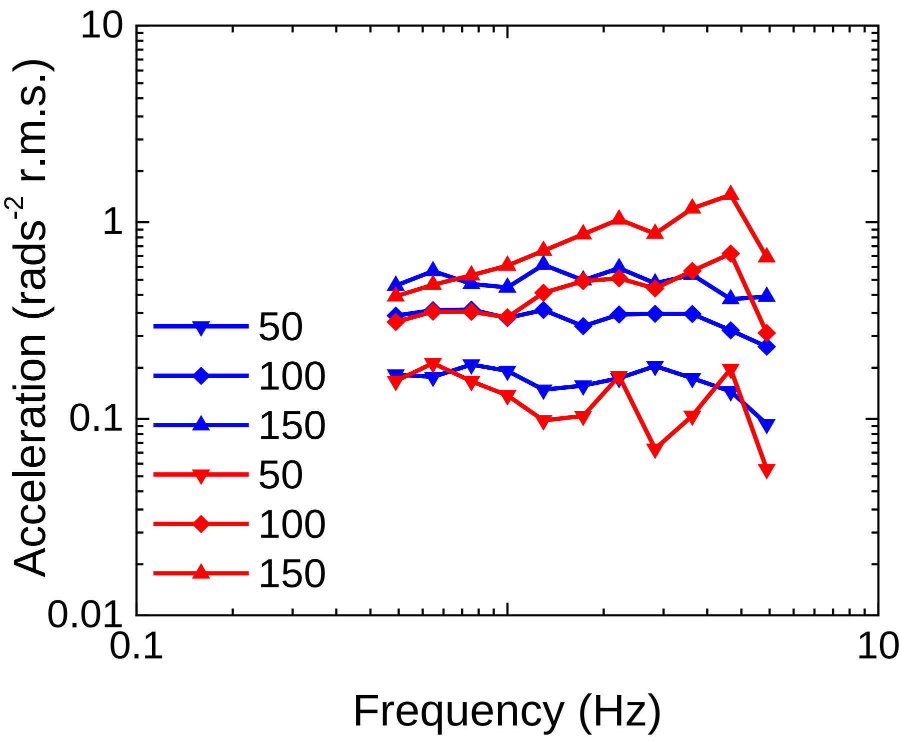

Figure 4.7 Comparison of equivalent comfort contours for a subjective magnitude ψ = 50, 100 and 150 in terms of unweighted r.m.s. pitch acceleration calculated from the median equivalent comfort contours of 15 subjects sitting with (blue) and without (red) a backrest.

4.4 Discussion

4.4.1 Rate of growth of discomfort

With no backrest, the rate of growth of discomfort decreased with increasing frequency of vibration. At lower frequencies, the rotational displacements were greater and so there was greater acceleration in the plane of the seat (i.e., g sin θ), which probably dominated discomfort. At higher frequencies, the rotational displacements were smaller and so the acceleration in the plane of the seat due to gravity was smaller, and the relative displacement between the moving legs and the torso was reduced, and there was no backrest to cause vibration discomfort at the back. In these conditions with higher frequency vibration and no backrest, the discomfort increased at a slower rate when the magnitude of vibration increased.

With the backrest, the rate of growth of discomfort was similar to that without backrest at low frequencies (less than 1.0 Hz), consistent with discomfort being caused by the same acceleration in the plane of the seat due to gravity in both cases. No significant effect of a backrest on the rate of growth of discomfort over the frequency range 0.2 to 1.6 Hz has previously been reported by Wyllie and Griffin (2009). In the present study, at frequencies greater than 1.0 Hz, the rate of growth of discomfort was greater with the backrest than without the backrest, consistent with backrest motion becoming a new important source of discomfort.

The variations in the rates of growth of discomfort over frequency and between backrest conditions are consistent with the rate of growth being greater when discomfort is dominated by factors affecting the whole body and less when discomfort is not localised in the torso (Jang and Griffin, 2000).

4.4.2 Equivalent comfort contours

The frequency-dependence in the rate of growth of discomfort caused the equivalent comfort contours to change shape according to the magnitude of the vibration. The effect was far greater without the backrest because the rate of growth of discomfort changed more over the frequency range 0.5 to 5 Hz when there was no backrest.

The difference in the rate of growth of discomfort between sitting with a backrest and sitting without a backrest (at frequencies greater than about 1.0 Hz) means that the extent to which the backrest increased discomfort depended on the magnitude of the vibration, as can be seen in Figure 4.7.

At frequencies less than about 1.0 Hz, the equivalent comfort contours with and without a backrest are similar, indicating that the rigid backrest had no overall negative or positive effect on the discomfort caused by pitch oscillation at these frequencies. Because the rate of growth was similar with and without a backrest at these frequencies it may be concluded that the negligible effect of the backrest on discomfort will apply over a wide range of magnitudes of pitch oscillation at frequencies less than about 1.0 Hz. At higher frequencies, the addition of the backrest increased discomfort, and the obvious cause is the contribution from fore-and-aft vibration of the backrest produced by the pitch oscillation of the seat pan. These findings are broadly consistent with those of Wyllie and Griffin (2009) who found increased discomfort with a backrest at frequencies greater than 0.63 Hz, although they did not investigate frequencies greater than 1.6 Hz.

To predict the discomfort caused by the fore-and-aft vibration at the back arising from pitch oscillation it is necessary to assume the effective height above the seat pan where the fore-and-aft backrest vibration has the contact with the body that causes discomfort within the body. The flat vertical backrest employed in this study extended 0.558 m above the seat pan, but subjects would not have been in contact with the backrest at the highest point on this backrest. Half way up the backrest, the fore-and-aft motion caused by pitch oscillation about the seat pan would have been half the magnitude of the fore-and-aft motion at the top of the backrest. Over the range of backrest heights where the back is in contact with a backrest, a reduction in backrest height will reduce fore-and-aft vibration of the back and reduce the discomfort arising from the fore-and-aft backrest vibration produced by pitch oscillation, and possibly increase the range of frequencies over which discomfort is similar with and without a backrest.

British Standard 6841:1987 states: "*Measurements on the seat-back should be made at the position with the greatest effective vibration in contact with the body*", whereas ISO 2631-1:1997 states: "*Measurements on the seat-back should be made in the area of principal support of the body*". Neither of these is sufficiently specific to identify where vibration between a backrest and the back should be measured.

In this study, the centre of pitch was located at the upper surface of the seat pan. If pitch motion of a vehicle is measured beneath a seat, the fore-and-aft vibration at the seat back arising from this pitch motion will tend to be greater, and the role of pitch motion of the vehicle in causing discomfort will also appear to be greater than implied here. Additionally, a non-rigid backrest will exhibit amplification of vibration at some frequencies and attenuation of vibration at some other frequencies (Basri and Griffin, 2014), further complicating the prediction of vibration discomfort caused by pitch oscillation.

4.4.3 Comparisons with previous work

Equivalent comfort contours for persons exposed to pitch oscillation have previously been constructed by Parsons and Griffin (1982). Figure 4.8 shows the median equivalent comfort contours produced by Parsons and Griffin (1982) compared with a contour equal to ψ = 100, normalised so that the two curves are equal at 1.0 Hz.

The curves show broad agreement with each other up to 4.0 Hz, however there may be somewhat greater sensitivity at frequencies greater than 2.0 Hz in the current study. It is possible that the difference arises from the feet moving together with the seat in this experiment but the feet being stationary in the previous experiment (Parsons and Griffin, 1982), as relative movement between the seat and feet can increase discomfort at low frequencies (Jang and Griffin, 2000).

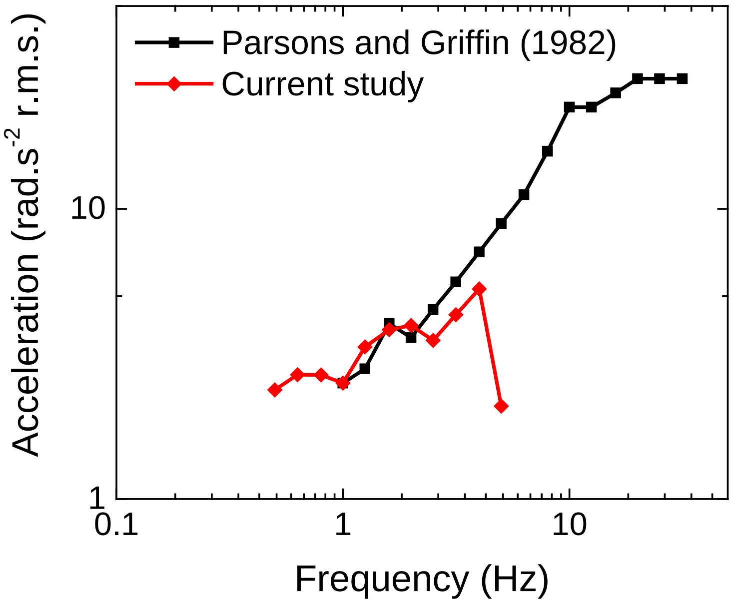

Figure 4.8 Comparison of median equivalent comfort contours of pitch oscillation without a backrest in terms of unweighted r.m.s. pitch acceleration from this study for a subjective magnitude of ψ = 100 and from Parsons and Griffin (1982). The acceleration magnitude for the current study has been adjusted to be equal to the previous study at 1.0 Hz.

At 5 Hz there is a large increase in sensitivity in the current study when compared to Parsons and Griffin (1982). Two reasons have been considered for this, firstly, the feet were stationary in the previous work whereas they were moving with the seat in the current work. As the feet were positioned away from the centre-of-rotation of the motion they would have experienced vertical and fore-and-aft motion arising from the pitch oscillation and the feet become more sensitive to both fore-and-aft and vertical motion around 5 Hz (Parsons *et al.*, 1982). Another possible explanation is that the current study used a lower magnitude range than Parsons and Griffin (1982). Whilst the graph from the present study above has been adjusted to be equal to that of the graph from Parsons and Griffin (1982) at 1 Hz, the curve was produced at much lower magnitude (see Figure 4.6, right). Because of the very low rate-of-growth of discomfort at 5 Hz in the present study, if the graph were produced at the same magnitude of Parsons and Griffin (1982) the curves would have greater similarity, however the Author decided it would be deceptive to produce an equivalent comfort contour at a magnitude out of the experimental range.

4.4.4 Frequency weighting

Current British and International Standards (BS 6841:1987 and ISO 2631-1:1997, respectively) advocate the use of the frequency weighting W_e in the evaluation of pitch oscillation at the seat base and the use of W_c for the evaluation of fore-and-aft vibration at a backrest. When predicting discomfort from multiple simultaneous inputs of vibration, the British Standard (BS 6841:1987) suggests the use of the root-sums-of-squares (r.s.s.) to combine the discomfort predicted, Parsons and Griffin (1978) found that the r.s.s. method adequately predicts discomfort arising from combined rotational and translational vibration. Figure 4.9 (left) shows results from this experiment with a backrest for a subjective value, ψ, of 150 compared with the r.s.s. of the reciprocal of the W_e and W_c weightings.

Figure 4.9 (right) shows the equivalent comfort contours from this experiment without a backrest for a subjective value, ψ, of 150 compared with the reciprocal of the W_e frequency weighting, normalised to the same value at 1 Hz.

It can be seen in the graphs shown in Figure 4.9 that the results of this experiment are broadly in agreement with the weightings from the standards. The results without a backrest are slightly underestimated at frequencies greater than about 2 Hz.

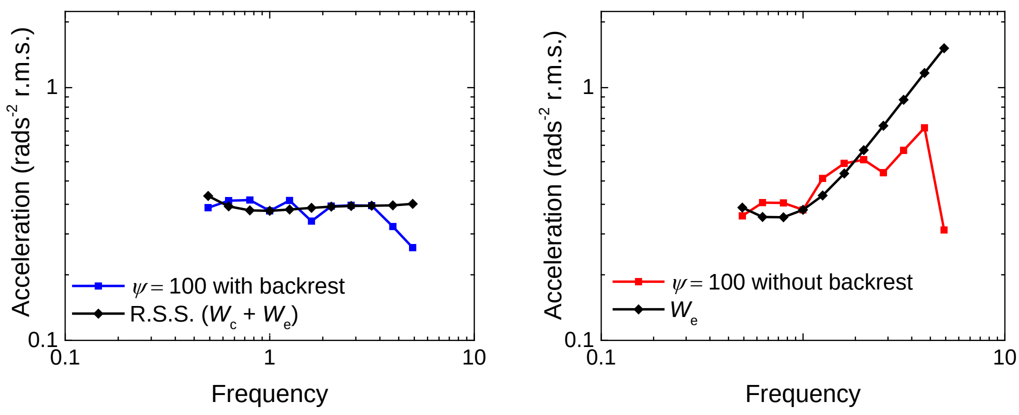

Figure 4.9 Comparisons of equivalent comfort contours ψ = 100 in terms of unweighted r.m.s. pitch acceleration and inverted weighting curves from BS 6841 (1987). Comparison between the condition with the backrest and an r.s.s. of W_c and W_e (left) and a comparison between the condition without the backrest and W_e (right). Reciprocal frequency weighting curves are normalised to be equal to equivalent comfort contours at 1 Hz.

4.5 Conclusions

The rate of growth of discomfort caused by pitch oscillation of a seat depends on the frequency of oscillation, and whether the seat has a backrest. The relative discomfort between frequencies and between seating conditions (backrest or no backrest) therefore depends on the magnitude of oscillation.

Although the appropriate frequency weighting depends on the magnitude of vibration, at frequencies greater than about 1.0 Hz a backrest will tend to increase the discomfort caused by pitch oscillation. At frequencies less than about 1.0 Hz, the discomfort caused by pitch oscillation seems to be similar with and without a backrest.

When fore-and-aft vibration at a backrest contributes to vibration discomfort, it should be recognised that the cause may be pitch motion of the vehicle. Pitch oscillation of the floor of a vehicle, how it is transmitted to drivers and passengers, and how it contributes to the perception of vehicle vibration discomfort merits greater consideration.

Chapter 5 Effect of reducing or removing a single axis of motion from a reproduced vehicle ride

5.1 Introduction

Standardised methods exist to measure, evaluate and assess vibration discomfort felt within a vehicle and are found in British Standard BS 6841 (1987) and International Standard ISO 2631-1 (1997). Using these methods it should be possible to predict increases and decreases in vehicle comfort from different ride values produced from measurements taken from within a vehicle or on a motion simulator.

There are many advantages of using a motion simulator for subjective ride comfort judgements over a real vehicle, such as the repeatability of the ride produced, a controlled external environment, and back-to-back analysis of various ride conditions. An additional advantage from using a motion simulator rather than a vehicle for ride comfort judgements is that it is possible to change the characteristics of a ride profile (magnitude, frequency spectra, duration etc.) simply and without the cost of changing parts on a vehicle, especially if the change is hard to achieve. This experiment was designed to see if participants could detect improvements in ride comfort resulting from reductions in vibration magnitude in different axes and if the detection could be predicted from measured ride evaluations.

Not all changes in vibration magnitude are detectable by humans. Weber's law suggests there is a minimum difference in a stimulus magnitude that can be detected by humans, and that this difference is a constant fraction of the stimulus (Gescheider, 1985). Morioka and Griffin (2000) investigated the difference thresholds of humans subjected to vertical sinusoidal at 5 Hz and 20 Hz with reference stimuli at 0.1 ms^{-2} and 0.5 ms^{-2} using the up-and-down transformed response (UDTR) method. It was found that whilst lower median difference thresholds were observed at 20 Hz than 5 Hz, there was no significant difference caused by either magnitude or frequency to the percentage difference threshold observed. Median difference thresholds ranged from 8.13% to 12.25% suggesting that a difference in magnitude greater than 10% should be detectable by humans.

Mansfield and Griffin (2000) observed a slightly higher difference threshold of around 13% (median range between 11.8% and 14.1%) when using complex vertical acceleration from a recorded vehicle ride, also using the UDTR method.

The effects of the magnitude and the frequency of whole-body vibration on Weber fractions were investigated by Forta *et al*., (2009). . Using three magnitudes at the preferred octave band centre frequencies from 2.5 to 315 Hz (0.05, 0.2 and 0.8 ms^{-2} r.m.s. at frequencies from 2.5 to 40 Hz, and magnitudes increasing in proportion to frequency at frequencies greater than 40 Hz) they found median Weber fractions from 9.5% to 20.3% with an overall median at 13.5%. It was also found that at the greatest magnitude investigated the median Weber fraction increased with increasing frequency from 2.5 to 40 Hz, and then decreased with increasing frequency from 40 to 315 Hz. Significant differences were seen at the lowest and highest frequencies (2.5 and 315 Hz) when investigating the effect of magnitude. It was thought that this may have arisen from subjects being able to see the difference in displacement at the lowest frequency and being able to hear the vibration at the highest frequency. At the intermediate frequencies, where changes in vibration could only be felt, there were no significant differences in Weber fraction with changing magnitude of vibration.

In this study, it was hypothesised that reductions in discomfort would only be detectable when there were reductions in vibration greater than the difference threshold of around 10% to 13.5% (Morioka and Griffin, 2000; Mansfield and Griffin, 2000; Forta *et al*., 2009). Additionally, it was hypothesised that any significant differences in judgements of vibration discomfort would reflect differences in objective evaluations of ride comfort.

5.2 Method

5.2.1 Participants

Fifteen healthy male students from the University of Southampton participated in the study. Their median age was 23 years (range 19 to 31 y), height 1.79 meters (range 1.65 to 1.94 m) and weight 75 kg (range 56 to 97 kg). The physical characteristics are reported in Table 5.1.

The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (application number 17546).

5.2.2 Motions

Motion stimuli were generated using MATLAB (version 2012a) and the *HVLab* toolbox (version 1). The 6-axis stimuli were created by using a single 10-second excerpt from a vibration recording of a Range Rover vehicle traveling down the B4100 road (relatively smooth) at 50 mph. The recorded weighted r.s.s. (root-sums-of-squares) value for this stimulus on the motion simulator was 0.352 ms^{-2} r.m.s. (1.038 $ms^{-1.75}$ VDV).

Table 5.1 Participant characteristics

Subject	Gender	Age (y)	Height (m)	Weight (kg)
1	M	25	1.65	75
2	M	29	1.80	90
3	M	24	1.94	85
4	M	29	1.86	90
5	M	24	1.85	97
6	M	20	1.83	75
7	M	23	1.70	71
8	M	23	1.84	76
9	M	22	1.88	84
10	M	20	1.74	62
11	M	31	1.72	65
12	M	24	1.70	71
13	M	19	1.69	56
14	M	20	1.79	63
15	M	19	1.77	63

Acceleration time histories were taken from accelerometers placed at each end of the two seat rails that secured the passenger seat in the Range Rover vehicle. The three translational directions of motion were taken from the corresponding acceleration recordings made at the front left corner of the front passenger seat rail.

Roll acceleration data was calculated from the difference between the front right and front left vertical accelerations, divided by the distance between them. Pitch acceleration data was calculated from the difference between the front left and rear left vertical acceleration data divided by the distance between them. Yaw acceleration data was calculated from the difference between the front left and front right fore-and-aft accelerometers.

The motion was tapered at the beginning and end to ensure a smooth start and finish of the simulator platform.

The 6-axis motion simulator used acceleration files as input, which was then analysed, reproduced and adjusted based on recordings of the motion produced. For this reason, it was appropriate to create separate files for each condition in MATLAB before exporting to the PULSAR system used to control the 6-axis simulator. The conditions to be tested were:

- Original full 6-axis signal.
- Original signal with 50% reduced fore-and-aft acceleration.
- Original signal with 50% reduced lateral acceleration.
- Original signal with 50% reduced vertical acceleration.
- Original signal with 50% reduced roll acceleration.
- Original signal with 50% reduced pitch acceleration.
- Original signal with 100% reduced fore-and-aft acceleration.
- Original signal with 100% reduced lateral acceleration.
- Original signal with 100% reduced vertical acceleration.
- Original signal with 100% reduced roll acceleration.
- Original signal with 100% reduced pitch acceleration.

Variations in yaw were not included because the amount of yaw was insufficient to expect it to cause significant discomfort.

Judgements of vibration discomfort were obtained using the method of paired comparisons. The method of paired comparisons increases the number of judgements with the number of conditions, with the number of judgements equal to the number of conditions multiplied by the number of conditions minus one when comparing each pair in both orders (A-B and B-A). The stimuli were therefore split into two groups for testing: part A) full original and all five 50% reduced conditions (i.e., where the magnitudes of each of the five stimuli were reduced to half the level recorded in the vehicle), and part B) full original and all five 100% reduced conditions (i.e., where the magnitudes of each of the five stimuli were reduced to zero). This created a total of 30 conditions for each part of the experiment. Acceleration time histories used as an input for the 6-axis motion are given in Figure 5.1 and an example comparison of the vertical motion in three conditions; original, 50% reduced and 100% reduced, are shown in Figure 5.2. Tables 5.1 and 5.2 detail the unweighted r.m.s. acceleration values achieved on the platform and Figure 5.2.5 shows the power spectra achieved on the platform.

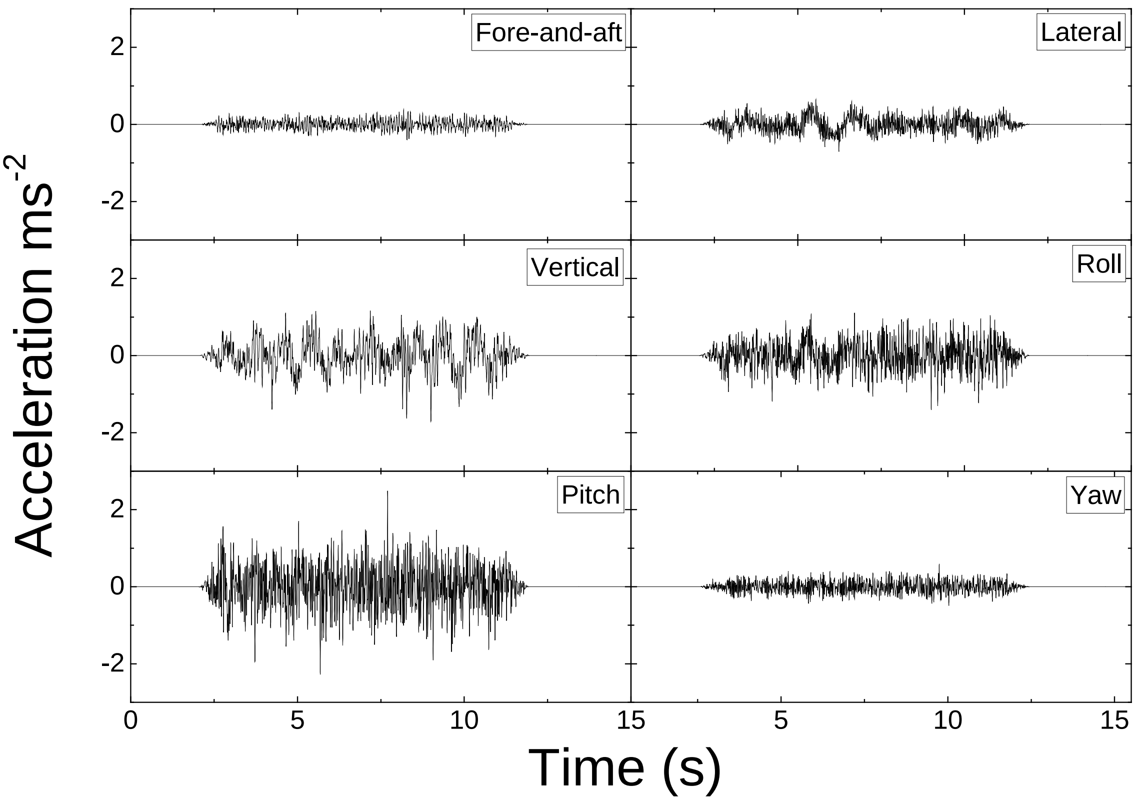

Figure 5.1 6-axis acceleration time histories from the original recorded ride used to drive the simulator.

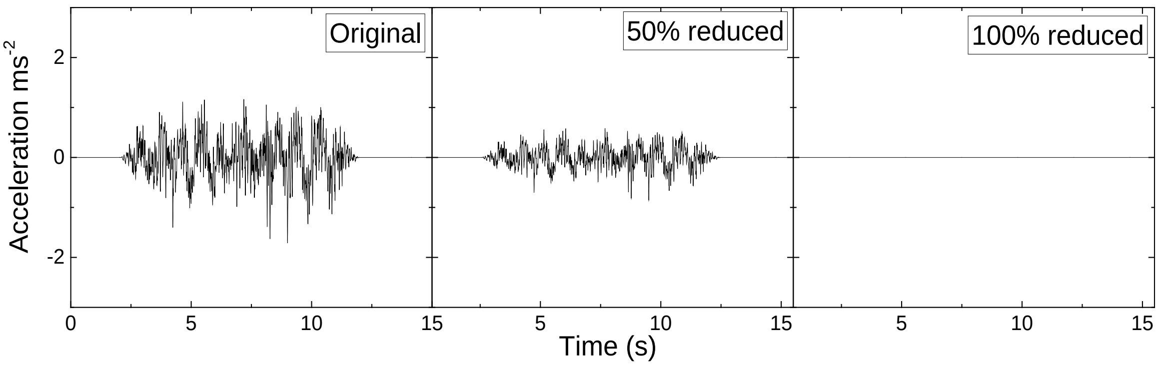

Figure 5.2 Vertical acceleration time histories at the original magnitude (left), 50% reduced magnitude (centre) and 100% reduced magnitude (right).

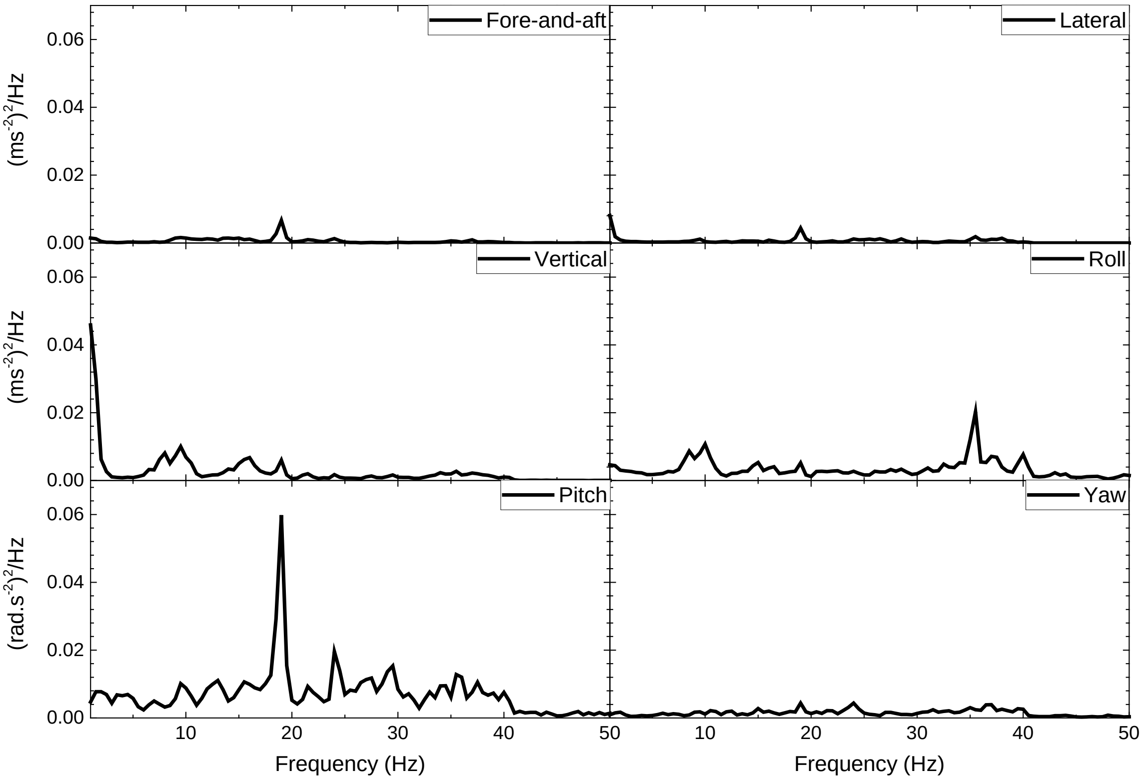

Figure 5.3 Unweighted 6-axis acceleration spectra recorded from the motion simulator.

Table 5.2 Unweighted r.m.s. acceleration magnitudes achieved at the base of the seat on the motion simulator in each of the 6 conditions from part A of the experiment.

Axis	Original motion	50% fore-and-aft reduction	50% lateral reduction	50% vertical reduction	50% roll reduction	50% pitch reduction
Fore-and-aft	0.156	0.135	0.154	0.150	0.155	0.142
Lateral	0.170	0.169	0.104	0.169	0.164	0.162
Vertical	0.353	0.360	0.352	0.221	0.367	0.335
Roll	0.583	0.651	0.579	0.585	0.566	0.524
Pitch	0.700	0.742	0.707	0.705	0.725	0.535
Yaw	0.292	0.329	0.324	0.348	0.321	0.298

Table 5.3 Unweighted r.m.s. acceleration magnitudes achieved at the base of the seat on the motion simulator in each of the 6 conditions from part B of the experiment.

Axis	Original motion	100% fore-and-aft reduction	100% lateral reduction	100% vertical reduction	100% roll reduction	100% pitch reduction
Fore-and-aft	0.156	0.095	0.129	0.114	0.129	0.111
Lateral	0.170	0.158	0.060	0.147	0.141	0.144
Vertical	0.353	0.347	0.344	0.160	0.368	0.297
Roll	0.583	0.635	0.638	0.470	0.633	0.439
Pitch	0.700	0.719	0.725	0.597	0.768	0.352
Yaw	0.292	0.315	0.317	0.270	0.300	0.219

5.2.3 Apparatus

The 6-axis complex motions were produced by the 6-axis precision motion simulator in the Human Factors Research Unit of the Institute of Sound and Vibration Research at the University of Southampton. Figure 5.3 shows the experimental setup.

A compliant Range Rover seat provided by Jaguar Land Rover was mounted on the simulator. The base of the seat was reclined by 12 degrees relative to the platform, the backrest was reclined, to be at 92 degrees relative to the seat base, and the headrest was removed. The centre of rotation was adjusted to be 150 mm beneath the centre of the seat at the mid-point between the seat rail mounting positions, as this is where the centre of rotation was calculated from rotational accelerations.

Subjects wore a loose lap belt and held an emergency stop button for safety. A rigid footrest mounted to the simulator (moving with the seat) was provided to keep subjects thighs parallel to the seat surface without motion.

Subjects wore headphones producing white noise at 65 dB (A) to mask sounds produced by the motion of the simulator. The experimenter communicated with the subjects via a microphone and the headphones.

Figure 5.4 Experimental setup on the 6-axis simulator

5.2.4 Procedure

Subjects attended one session lasting around 60 minutes, which included reading instructions, signing a consent form, practice, and participating in the experiment. They received written instructions, had a chance to practice and a chance to ask any questions they had about the experiment. The practice consisted of experiencing five motions and judging differences in vibration discomfort with the same six-point scale that was used for the rest of the experiment.

During the experiment, the subjects were instructed to close their eyes to eliminate the visual perception of motion from their evaluations. They were instructed to sit comfortably in the seat and rest their hands in their lap and maintain contact with the backrest at all times.

Subjects rated the discomfort of pairs of stimuli using the paired comparison method. Each possible pair within the group of stimuli (see Tables 5.2 and 5.3) were tested in both ‘A-B’ and ‘B-A’ configurations. The order of presenting the stimuli was randomised and each subject received a different random order.

Each subject was presented a total of 60 pairs of stimuli, all possible combinations of two groups of six, in two parts of the experiment as detailed above. The subjects were told that the next pair of stimuli would start a few seconds after they gave a response and that there was a 5-second gap between the pair being presented (Figure 5.4).

Table 5.4 Summary of pairs of stimuli in part A.

		2nd Stimulus					
1st Stimulus		Full original	Fore-and-aft 50% reduced	Lateral 50% reduced	Vertical 50% reduced	Roll 50% reduced	Pitch 50% reduced
	Full original		X	X	X	X	X
	Fore-and-aft 50% reduced	X		X	X	X	X
	Lateral 50% reduced	X	X		X	X	X
	Vertical 50% reduced	X	X	X		X	X
	Roll 50% reduced	X	X	X	X		X
	Pitch 50% reduced	X	X	X	X	X	

Table 5.5 Summary of pairs of stimuli in part B.

		2nd Stimulus					
1st Stimulus		Full original	Fore-and-aft 100% reduced	Lateral 100% reduced	Vertical 100% reduced	Roll 100% reduced	Pitch 100% reduced
	Full original		X	X	X	X	X
	Fore-and-aft 100% reduced	X		X	X	X	X
	Lateral 100% reduced	X	X		X	X	X
	Vertical 100% reduced	X	X	X		X	X
	Roll 100% reduced	X	X	X	X		X
	Pitch 100% reduced	X	X	X	X	X	

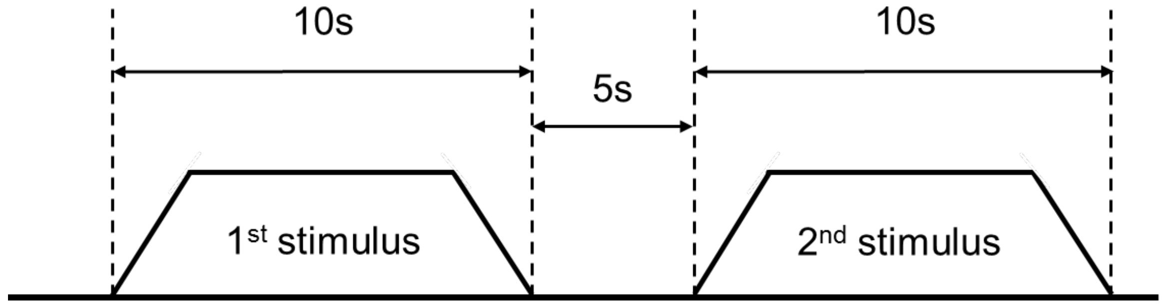

Figure 5.5 Example of presentation of stimulus pair.

The subjects compared each pair of stimuli in terms of perceived whole body discomfort, they gave their ratings using the 6-point category scale:

+3: The first motion caused very much more discomfort than the second motion.

+2: The first motion caused much more discomfort than the second motion.

+1: The first motion caused slightly more discomfort than the second motion.

-1: The second motion caused slightly more discomfort than the first motion.

-2: The second motion caused much more discomfort than the first motion.

-3: The second motion caused very much more discomfort than the first motion.

The procedure was repeated 60 times (with one break) until all combinations had been presented. The subjects were allowed to repeat any pair they wished during the experiment. The background noise was presented to the subjects throughout the experiment. The subjects were provided written instructions that are shown in Appendix A.

5.2.5 Data analysis

A typical data set from a subject is shown in Table 5.6. Positive numbers correspond to the first stimulus being more uncomfortable than the second, and negative numbers correspond to the second stimulus being more uncomfortable than the first.

Table 5.6 Summary of subject 1's response to stimuli in part A.

		2nd Stimulus					
		Full original	Fore-and-aft 50% reduced	Lateral 50% reduced	Vertical 50% reduced	Roll 50% reduced	Pitch 50% reduced
1st Stimulus	Full original		-1	-1	-2	-1	-2
	Fore-and-aft 50% reduced	1		-1	1	-1	1
	Lateral 50% reduced	1	-2		-1	-1	-1
	Vertical 50% reduced	1	-1	-1		-1	1
	Roll 50% reduced	-1	-2	-2	-2		-1
	Pitch 50% reduced	-1	1	-2	-1	-1	

Analysis of the subjective data was carried out using Scheffe's method of paired comparisons (Muria *et al.*, 1973). The procedure was carried out according to the description provided by Ebe (1998) and detailed in Chapter 3.

5.2.6 Statistical tests

Probabilities were calculated using the ANOVA F-test and Scheffe's method of paired comparisons.

5.3 Results

5.3.1 Summary of the analysis of variance

Tables 5.7 and 5.8 show the summary of variance for the perceived discomfort for the 50% reduction and the 100% reduction conditions respectively. In Tables 5.7 and 5.8 the degrees of freedom are '*the number of 'entities' that are free to vary when estimating some kind of statistical parameter'* (Field, 2009) and depends on the sample size of the effect under observation (e.g. primary, combination and order). The F statistic is defined as the quotient between the variance of the effect being tested and the variance of the error.

Table 5.7 Summary of the analysis of variance for the perceived discomfort in the 50% reduction condition.

	Sum of squares	Degrees of freedom	Variance	F	Significance
Primary	12.93	5	2.59	1.31	$p > 0.05$
Combination	27.07	10	2.71	1.38	$p > 0.05$
Order	111.60	15	7.44	3.78	$p < 0.001$
Error	826.40	420	1.97		
Total	978.00	450			

Table 5.8 Summary of the analysis of variance for the perceived discomfort in the 100% reduction condition.

	Sum of squares	Degrees of freedom	Variance	F	Significance
Primary	25.01	5	5.00	2.43	$p < 0.05$
Combination	64.49	10	6.45	3.14	$p < 0.001$
Order	152.57	15	10.17	4.95	$p < 0.001$
Error	863.60	420	2.06		
Total	1105.67	450			

It can be seen from Tables 5.7 and 5.8 that the primary effect and the combination effect is not significant with 50% reduction in any axis, although the primary effect and the combination effect are significant with 100% reduction. In addition, there were significant effects of order in both conditions, meaning that the subjective judgements were influenced by the order of presenting pairs of stimuli. The second stimulus was judged as significantly more uncomfortable than the first stimulus.

5.3.2 Comfort score

The average comfort score from the subjects (α_i) is determined by the following equation:

$$\alpha_i = (x_{i..} - x_{.i.}) / (2tp) \quad (5.1)$$

where $x_{i..}$ is the cumulative score when α_i is the second stimulus, $x_{.j.}$ is the cumulative score when α_i is the first stimulus, t is the number of stimuli, and p is the number of participants. Full details of the calculations are given in Appendix B. For example, the comfort score for the full 6-axis stimulus during the first half of the experiment was:

$$\alpha_{B4100\_full} = (-6 - -9) / (2 \times 6 \times 15) = 0.017 \quad (5.2)$$

The average comfort scores are given in Table 5.9 and are shown graphically in Figures 5.6 and 5.7. It can be seen that reducing lateral and roll motion had the greatest effect on the comfort score. It can be seen that a reduction in lateral acceleration was preferred by participants in both groups of pairs and that a reduction in fore-and-aft acceleration was the least preferred.

Table 5.9 Summary of comfort scores of each condition

Ride condition	Comfort score	Ride condition	Comfort score
Full ride	0.017	Full ride	-0.089
50% fore-and-aft reduction	-0.117	100% fore-and-aft reduction	-0.161
50% lateral reduction	0.200	100% lateral reduction	0.233
50% vertical reduction	-0.106	100% vertical reduction	-0.078
50% roll reduction	0.061	100% roll reduction	0.189
50% pitch reduction	-0.056	100% pitch reduction	-0.094

To discover whether the differences between individual pairs of stimuli are significant or not, a 'yardstick' Y_{Φ}, was calculated from the equation:

$$Y_{\Phi} = q_{\Phi}(t, f_e) \times ((\sigma^2 / 2nt))^{½} \quad (5.3)$$

where:

q_{Φ} is the percentage points of the Studentized range,

Φ is the significance level,

f_e is the degree of freedom for error

σ^2 is the variance of the error.

From a table in Kirk (1968), $q_{0.05}(t,f_e) = 4.063$ and $q_{0.01}(t,f_e) = 4.814$

where $t = 6$ and $f_e = 240$. Whilst in this study, f_e is actually 420, 240 is used as the highest number quoted below infinity. For the case of 50% reduction, the yardstick for confidence levels of 0.05 and 0.01 are:

$Y_{0.05} = 4.063 \times (1.97 / (2 \times 15 \times 6))^{½} = 0.425$

$Y_{0.01} = 4.814 \times (1.97 / (2 \times 15 \times 6))^{½} = 0.503$

For the case of 100% reduction, the yardstick for confidence levels of 0.05 and 0.01 are:

$Y_{0.05} = 4.063 \times (2.06 / (2 \times 15 \times 6))^{½} = 0.434$

$Y_{0.01} = 4.814 \times (2.06 / (2 \times 15 \times 6))^{½} = 0.515$

If the difference between two comfort scores is greater than the yardstick, this means that there is a significant difference between the two stimuli. Tables 5.8 and 5.9 and Figures 5.5 and 5.6 show that the differences in comfort score between each condition are below the yardstick for each condition and therefore no significant differences exist between pairs of stimuli.

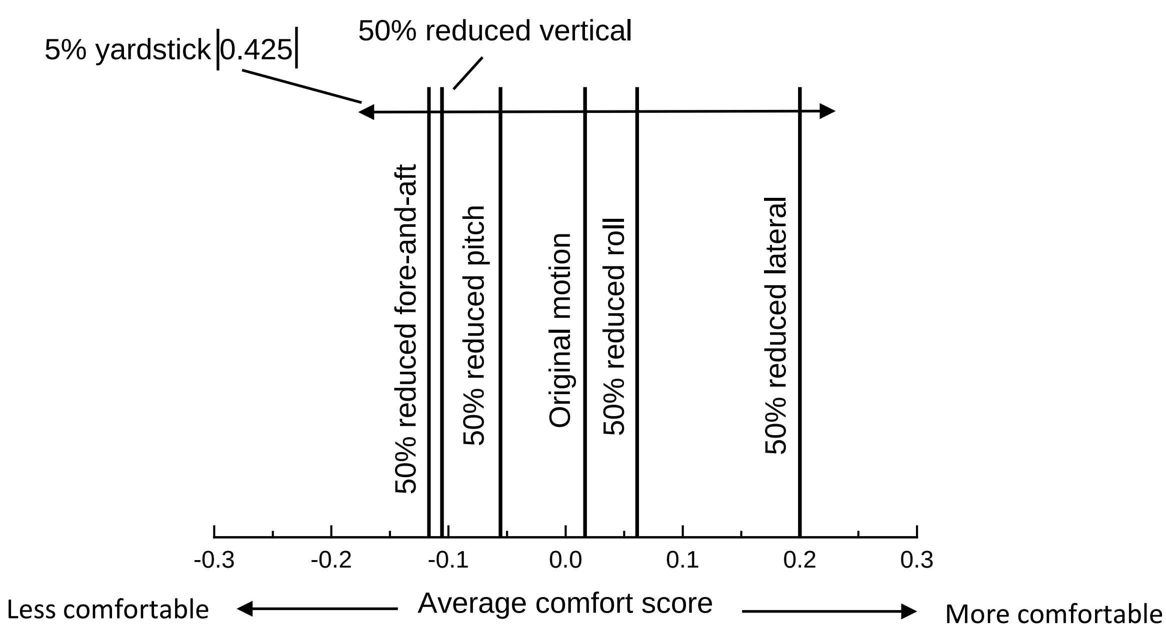

Figure 5.6 Average comfort scores in the 50% reduction group.

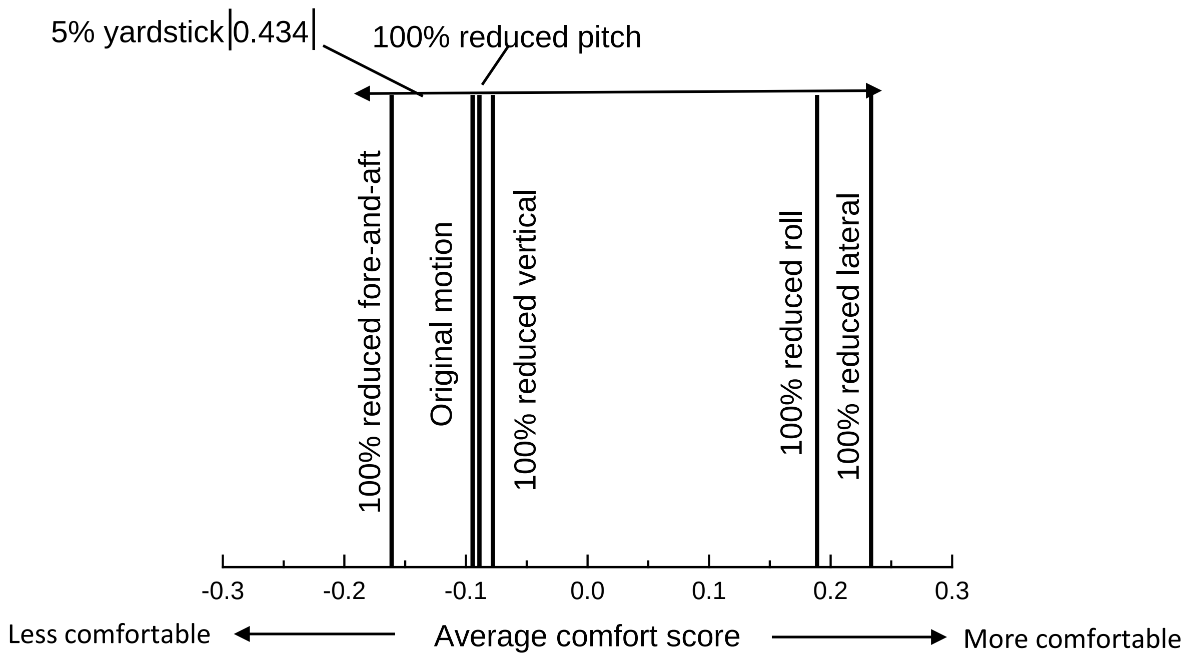

Figure 5.7 Average comfort scores in the 100% reduction group.

Table 5.10 Absolute difference in comfort scores within the 50% reduction group.

Ride condition	50% fore-and-aft reduction	50% lateral reduction	50% vertical reduction	50% roll reduction	50% pitch reduction
Full ride	0.133	0.183	0.122	0.044	0.072
50% fore-and-aft reduction		0.317	0.011	0.178	0.061
50% lateral reduction			0.306	0.139	0.256
50% vertical reduction				0.167	0.050
50% roll reduction					0.117

Table 5.11 Absolute difference in comfort scores within the 100% reduction group.

Ride condition	100% fore-and-aft reduction	100% lateral reduction	100% vertical reduction	100% roll reduction	100% pitch reduction
Full ride	0.072	0.322	0.011	0.278	0.006
100% fore-and-aft reduction		0.394	0.083	0.350	0.067
100% lateral reduction			0.311	0.044	0.328
100% vertical reduction				0.267	0.017
100% roll reduction					0.283

5.3.3 Recorded ride

To try to understand the insignificant primary effect in the experiment, vibration was measured on the seat and floor on the simulator. Vibration on the seat was measured using SIT-pads on the seat surface underneath the subject's ischial tuberosities and between the subject and the backrest at the height where the subject felt greatest contact with the backrest. Vertical accelerometers were placed at all four locations on the seat rails attached to the simulator to measure vertical, roll, and pitch accelerations. Fore-and-aft accelerometers were placed on the front two seat rails to measure fore-and-aft and yaw acceleration, and a lateral accelerometer was attached to the front left seat rail to measure lateral acceleration.

These data were required to investigate the input to the human body, mitigate any errors of the simulator when producing rides (as the ride felt by the subject was recorded rather than just the input), and consider the effect of the seat dynamics.

Tables 5.12 and 5.13 show the overall 6-axis weighted r.m.s. accelerations and vibration dose values (VDV's) for the conditions with 50% reduction and 100% reduction respectively. Ride values were calculated using frequency weightings and axis multiplying factors found in British Standard 6841 (1987) and used the root-sums-of-squares (r.s.s.) summation method.

Table 5.12 Frequency weighted and axis weighted measured r.m.s. acceleration magnitudes achieved at the seat, backrest and floor of the motion simulator in each of the 6 conditions from part A of the experiment.

Axis	Original motion	50% fore-and-aft reduction	50% lateral reduction	50% vertical reduction	50% roll reduction	50% pitch reduction
Seat fore-and-aft	0.092	0.087	0.091	0.058	0.092	0.091
Seat lateral	0.089	0.089	0.052	0.086	0.092	0.089
Seat vertical	0.195	0.200	0.197	0.122	0.215	0.182
Seat roll	0.043	0.062	0.053	0.056	0.036	0.053
Seat pitch	0.034	0.038	0.035	0.039	0.038	0.023
Seat yaw	0.007	0.009	0.008	0.008	0.008	0.008
Backrest fore-and-aft	0.236	0.236	0.236	0.148	0.241	0.215
Backrest lateral	0.044	0.044	0.028	0.045	0.046	0.044
Backrest vertical	0.044	0.040	0.040	0.036	0.042	0.029
Floor fore-and-aft	0.029	0.023	0.028	0.027	0.029	0.027
Floor lateral	0.026	0.026	0.016	0.026	0.025	0.025
Floor vertical	0.094	0.095	0.093	0.054	0.100	0.089
Overall (r.s.s.)	0.356	0.361	0.348	0.244	0.374	0.333

Table 5.13 Frequency and axis weighted measured r.m.s. acceleration magnitudes achieved at the seat, backrest and floor of the motion simulator in each of the 6 conditions from part B of the experiment.

Axis	Original motion	100% fore-and-aft reduction	100% lateral reduction	100% vertical reduction	100% roll reduction	100% pitch reduction
Seat fore-and-aft	0.092	0.083	0.089	0.042	0.090	0.088
Seat lateral	0.089	0.089	0.039	0.080	0.091	0.086
Seat vertical	0.195	0.186	0.187	0.110	0.209	0.157

Seat roll	0.043	0.055	0.057	0.053	0.025	0.053
Seat pitch	0.034	0.034	0.034	0.035	0.035	0.011
Seat yaw	0.007	0.008	0.009	0.007	0.007	0.006
Backrest fore-and-aft	0.236	0.242	0.240	0.112	0.254	0.200
Backrest lateral	0.044	0.046	0.026	0.046	0.047	0.045
Backrest vertical	0.044	0.049	0.050	0.042	0.052	0.026
Floor fore-and-aft	0.029	0.015	0.022	0.020	0.023	0.020
Floor lateral	0.026	0.025	0.009	0.023	0.022	0.023
Floor vertical	0.094	0.087	0.085	0.045	0.098	0.074
Overall (r.s.s.)	0.356	0.353	0.343	0.209	0.377	0.303

Table 5.14 Summary of the overall weighted r.m.s. acceleration and VDV's obtained from the ride generated from the platform and the comfort score obtained from the condition with 50% reduction in each axis.

Ride condition	Weighted r.m.s. (ms^{-2})	Weighted VDV ($ms^{-1.75}$)	Comfort score
Full ride	0.356	1.051	0.017
50% fore-and-aft reduction	0.361	1.062	-0.117
50% lateral reduction	0.348	1.023	0.200
50% vertical reduction	0.244	0.726	-0.106
50% roll reduction	0.374	1.103	0.061
50% pitch reduction	0.333	1.011	-0.056

Table 5.15 Summary of the overall weighted r.m.s. acceleration and VDV's obtained from the ride generated from the platform and the comfort score obtained from the condition with 100% reduction in each axis.

Ride condition	Weighted r.m.s. (ms^{-2})	Weighted VDV ($ms^{-1.75}$)	Comfort score
Full ride	0.356	1.051	-0.089
100% fore-and-aft reduction	0.353	1.060	-0.161
100% lateral reduction	0.343	1.022	0.233
100% vertical reduction	0.209	0.630	-0.078
100% roll reduction	0.377	1.135	0.189
100% pitch reduction	0.303	0.896	-0.094

Table 5.16 Percentage differences in evaluated ride scores within the 50% reduction group.

Ride condition	Full ride	50% fore-and-aft reduction	50% lateral reduction	50% vertical reduction	50% roll reduction	50% pitch reduction
Full ride	--	1.404	-2.247	-31.461*	5.056	-6.461
50% fore-and-aft reduction	-1.385	--	3.601	32.410*	3.601	7.756
50% lateral reduction	2.299	3.736	--	29.885*	7.471	4.310
50% vertical reduction	45.902*	47.951*	42.623*	--	53.279*	36.475*
50% roll reduction	-4.813	-3.476	-6.952	-34.759*	--	-10.963
50% pitch reduction	6.907	8.408	4.505	-26.727*	12.312	--

* Greater than the 13.5% difference threshold seen in Morioka and Griffin (2000) Mansfield and Griffin (2000) and Forta *et al* (2009).

Table 5.17 Percentage differences in evaluated ride scores within the 100% reduction group.

Ride condition	Full ride	100% fore-and-aft reduction	100% lateral reduction	100% vertical reduction	100% roll reduction	100% pitch reduction
Full ride	--	-0.843	-3.652	-41.292*	5.899	-14.888*
100% fore-and-aft reduction	0.850	--	-2.833	-40.793*	6.799	-14.164*
100% lateral reduction	3.790	2.915	--	-39.067*	9.913	-11.662
100% vertical reduction	70.335*	68.900*	64.115*	--	80.383*	44.976*
100% roll reduction	-5.570	-6.366	-9.019	-44.562*	--	-19.629*
100% pitch reduction	17.492*	16.502*	13.201	-31.023*	24.422*	--

* Greater than the 13.5% difference threshold seen in Morioka and Griffin (2000) Mansfield and Griffin (2000) and Forta *et al* (2009).

5.4 Discussion

5.4.1 Seat transmissibility

This study employed a non-rigid car seat for participants to sit on during the vibration motion. The compliant surface of non-rigid seats can offer static pressure relief to the occupant by spreading out overall pressure. However, compliant seats also behave differently within a dynamic environment by amplifying motions at certain frequencies and attenuating them at others, with the seat and occupant acting as a complex mass-spring-damper system. In addition, the geometry of the seat and fixings between the rigid parts of the seat will also alter the spectra of the motions experienced by the occupant.

Because of the non-rigid properties of the seat, the vibration spectra and magnitudes experienced by participants was different from that at the input of the seat (the platform of the simulator). For example, Figure 5.8 shows the power spectra for vertical acceleration at the floor and the seat surface. It can be seen that there is a resonance in the seat surface at 4.5 Hz and other frequencies are attenuated. Vibration was therefore measured at the interfaces between the occupant and seat surfaces for each of the motions and the frequency-weighted acceleration levels are reported in Tables 5.12 and 5.13.

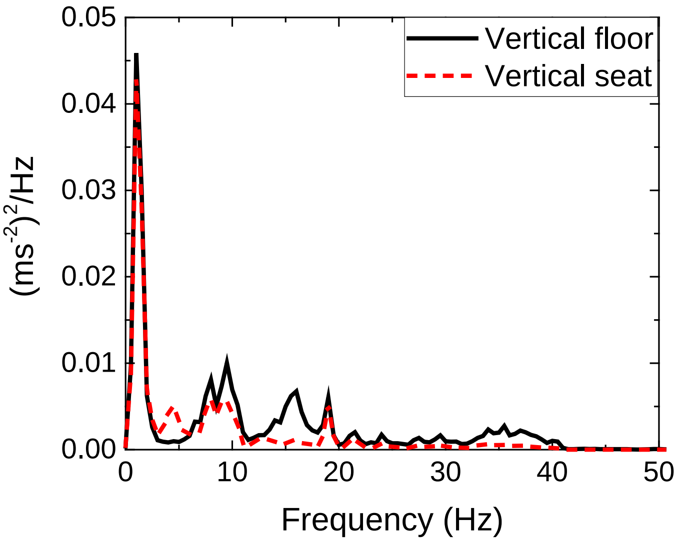

Figure 5.8 Unweighted vertical acceleration spectra recorded from the simulator floor and the seat surface.

5.4.2 Summary of variance

Whilst the initial *F*-test suggested a significant difference in the primary effect in the group of pairs involving 100% reductions in each axis, the Scheffe's method post-hoc test has shown that no individual ride was significantly more comfortable than any other ride. This suggests that, despite differences in the evaluated 6-axis motions shown in Tables 5.16 and 5.17, which exceed the difference thresholds reported by Morioka and Griffin (2000), Mansfield and Griffin (2000) and Forta *et al* (2009), subjects did not report experiencing less discomfort on rides producing the lowest levels of overall weighted magnitude than the rides producing the greatest overall magnitudes.

Within both groups of paired data (50% reduction in each axis and 100% reduction in each axis) there are highly significant order effects, with the second stimulus of each pair being described as more uncomfortable more often than the first stimulus. This bias has been observed previously in Griffin and Whitham (1980a) with subjects also more often choosing the second stimulus of a pair as more uncomfortable. It is possible that this effect could have been reduced by using the modified method of constant stimuli (Griffin *et al*., 1982a). The modified method of constant stimuli (in which both pairs are presented twice before asking for a judgement) was not chosen for this experiment because it would have doubled the duration of the experiment.

5.4.3 Comfort scores

The overall ride evaluated from objective data suggest that in the 50% reduction group, a reduction in vertical motion should reduce discomfort compared with all other conditions by more than the 13.5% difference threshold (Forta *et al.*, 2009). In the 100% reduction group, the stimulus with the reduced vertical motion and the stimulus with the reduced pitch motion should be more comfortable than all other stimuli, except between the motion with pitch reduction and the motion with lateral reduction, by a difference greater than the difference threshold (see Tables 5.16 and 5.17). Additionally the overall ride of the reduced vertical motion was less than that of the reduced pitch motion by more than the difference threshold. However, as none of the comfort scores differ by an amount greater than the yardstick in Section 5.3.2, participants did not reliably feel these motions as more comfortable than any other motion within either group of pairs.

Figures 5.9 and 5.10 compare the overall weighted r.m.s. values for each ride in each condition. If the results showed a significant difference in comfort score, it would be expected that with increasing comfort score the weighted r.m.s. would decrease. In both graphs this is not the case, with the lowest magnitude motion (reduced vertical vibration) not having a greater comfort score. As the results do not show a significant difference it is possible that either there was not enough statistical power to show the effect or the systematic effect of another variable (e.g., the order effect), whose influence was unexpected and therefore not adequately controlled, affected the results.

5.4.4 Recorded ride

The ride achieved on the platform was not an exact match to the ride time histories created in MATLAB. This is shown in the individual axis ride values seen in Tables 5.12 and 5.13 and in the overall values seen in Tables 5.14 and 5.15. It can be seen that where reductions in vibration magnitude were expected, the overall weighted magnitude increased in the 50% reduced fore-and-aft, and reduced roll stimuli for both reduction levels. This is perhaps caused by bending in the floor of the vehicle where the recording was made not being able to be reproduced on the rigid simulator platform and the control software trying to reduce the total error between the motion that it is trying to reproduce and the motion it can reproduce. In addition, the performance of the non-rigid seat must be accounted for and therefore the evaluated ride comfort used accelerations recorded from the simulator rather than the desired profile.

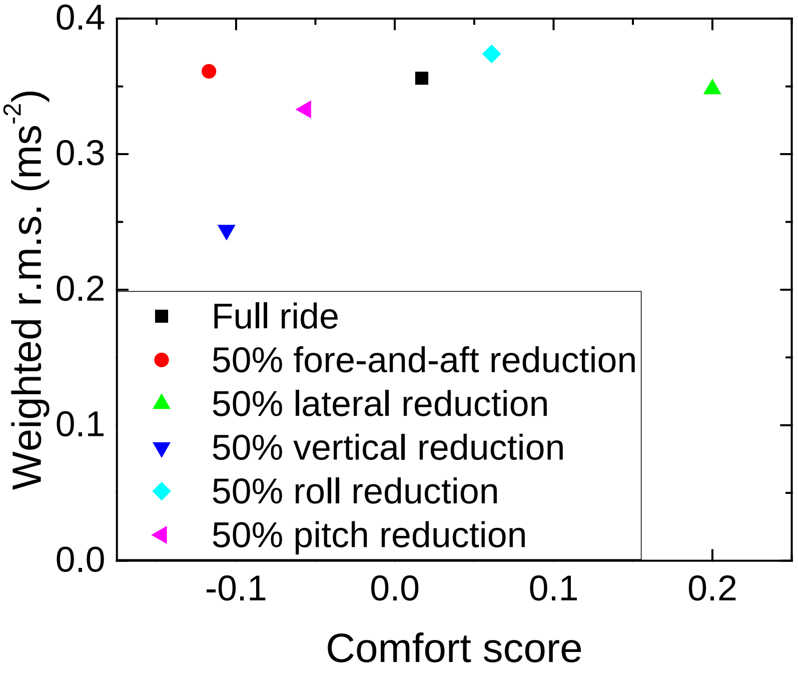

Figure 5.9 Comfort score compared with weighted r.m.s. vibration magnitude for the conditions with 50% reduction in vibration magnitude.

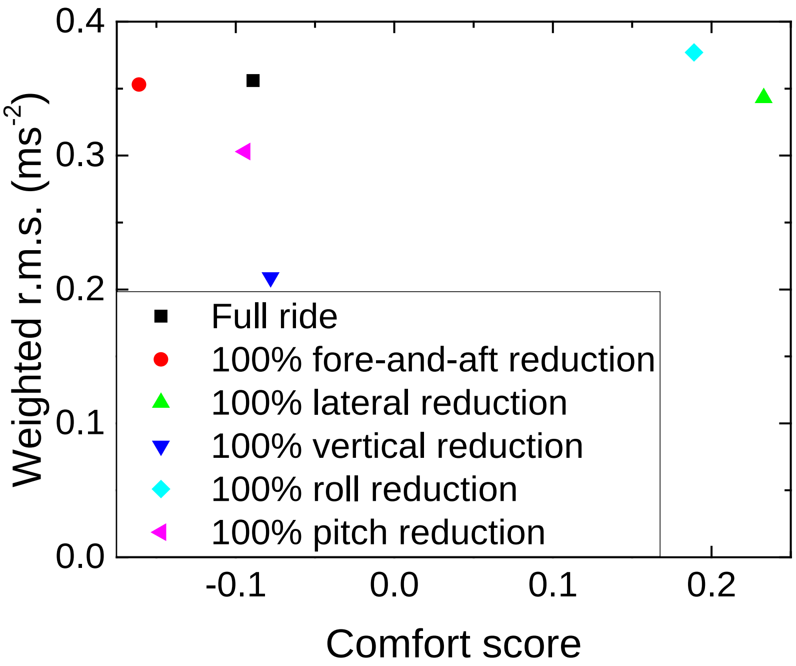

Figure 5.10 Comfort score compared with weighted r.m.s. vibration magnitude for the conditions with 100% reduction in vibration magnitude.

It can be seen from Figure 5.11 that in the condition with 100% reduced roll, the vertical direction power spectrum is similar in both conditions, with a lower maximum peak at 1 Hz with the 100% reduced roll condition but with slightly increased energy around 10 Hz, which the human body is sensitive to if this translates through the seat. Most of the increased energy in the roll axes in the

100% reduced roll condition is at high frequency, which the human body is not as sensitive to, and the motion at low frequency is reduced as expected. In the pitch direction, there is an increase in energy in the 100% reduced roll condition in the 0 to 40 Hz range except at the maximum peak at 19 Hz. This energy could increase discomfort if translated to vertical seat and fore-and-aft backrest vibration through the seat geometry.

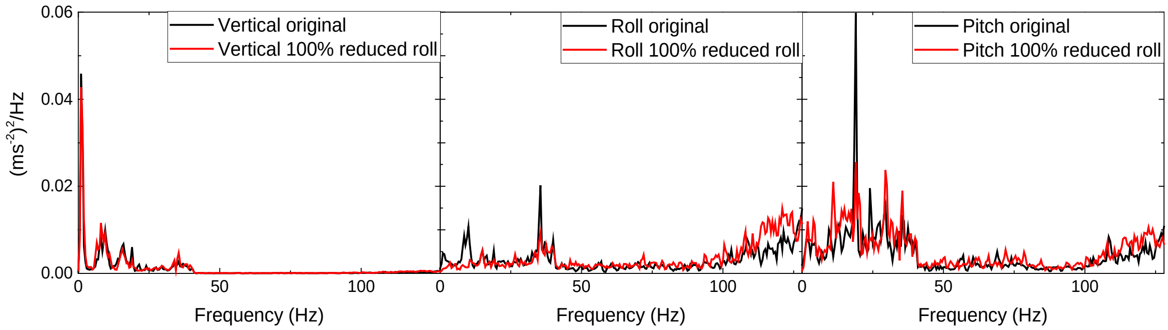

Figure 5.11 Unweighted vertical, roll and pitch acceleration spectra recorded from the motion simulator.

Despite the desired motion not being achieved on the platform exactly, the comparisons of the objectively evaluated ride and subjective comfort score were between the acceleration experienced by the participants during the experiment and the response provided by each subject. Because of this, the conclusions reached from this experiment are not affected by the performance achieved on the platform in this study.

5.4.5 Possible reasons for non-significant differences between stimuli

As the difference threshold was exceeded by the differences in overall ride values for some pairs of stimuli within both groups of stimuli, it is necessary to investigate reasons for participants not reliably choosing the stimulus with the lowest overall ride value as being the most comfortable.

The large order effect in this experiment may be masking the primary effect and reducing the order effect by repeating the pairs of stimuli might result in participants choosing the ride with the lowest overall ride value as the most comfortable ride. Also, the current experimental design and statistical analysis may not have had sufficient power to exclude the null hypothesis.

The evaluated differences in vibration magnitude between some pairs of stimuli were greater than the difference threshold observed by Morioka and Griffin (2000), Mansfield and Griffin (2000) and Forta *et al*. (2009). However, the differences between the rides experienced by the participants were not greater than their subjective difference thresholds and therefore the current evaluation procedure may not adequately reflect the vibration discomfort experienced during these simulations.

Conditions where vertical vibration was reduced should have reduced the overall ride by greater than the difference thresholds observed previously. In certain circumstances, Forta *et al.* (2009) found that the magnitude and the frequency affected the difference thresholds in vertical vibration. Whilst out of scope for this thesis, difference thresholds for vertical vibration in the presence of other axes of vibration require further investigation. Additionally, some participants reported the vibration with reduced vertical vibration as feeling 'unnatural' and this may have contributed to the low comfort score provided for these motions.

Participants in this study received no formal training in evaluating ride comfort. It is possible that differences between the stimuli may be detectable by a trained professional, but not the general public, especially if they are not aware of certain characteristics they should be feeling. Previous studies (Morioka and Griffin, 2000; Forta *et al.,* 2009; Mansfield and Griffin, 2000) used a single axis of motion and the method ensured that differences between motions increased until participants could reliably distinguish between them. This may have allowed the participants to acclimatise to each motion and look for specific characteristics in the feeling of the motion to determine which of each pair was greater in magnitude. In this study, a single axis of a 6-axis motion was reduced at random, with inputs at the seat, backrest, and feet, and each motion was compared with every other motion rather than with a control. It is arguable that the task in this study was more difficult than previous studies, and that a greater difference in magnitude is required using the methodology used in this experiment.

The rate-of-growth of discomfort affects the frequency-dependence of vibration discomfort (see Chapters 2 and 4) and the current prediction methods do not reflect the magnitude-dependence of the frequency-dependence of vibration discomfort. In addition, the inter-axis equivalence of discomfort between axes of vibration may depend on the magnitude of vibration if the rate-of-growth of discomfort is different between axes. This may increase the importance of some axes of vibration in some conditions and so the current standards may not provide optimum predictions of vibration discomfort in all conditions.

The standards use the r.s.s. summation method for summing vibration over different axes and input locations. The r.s.s. method has been found to be adequate for sinusoidal dual-axis motions when using objective evaluation methods (e.g. Griffin and Whitham 1977; Fairley and Griffin, 1988; and Mistrot *et al*., 1990), however it is yet to be demonstrated as adequate for complex dual-axis and tri-axial motion stimuli. If the summation of vibration over axes differs from an r.s.s.

Chapter 5 Effect of reducing or removing a single axis of motion from a reproduced vehicle ride model, this could have resulted in the difference threshold being exceeded without subjects noticing the difference.

5.5 Conclusions

Current whole-body vibration discomfort evaluation methods predicted differences in vibration magnitude arising from reductions in the vertical and pitch axes of vibration that exceeded the difference thresholds observed by Morioka and Griffin (2000), Mansfield and Griffin (2000), and Forta *et al.* (2009), but not by reductions in other axes.

Difference thresholds for vertical vibration during 6-axis motion have yet to be investigated and may be greater than those reported by previous studies using single axis motion. Whilst out of scope for this thesis, this area merits further consideration.

Two questions arise from this experiment that are within the scope of this thesis and require further investigation. Firstly, does the rate of growth of discomfort differ between axes of vibration and, if so, is this sufficient to affect the inter-axis equivalence of discomfort between the axes? Secondly, is the r.s.s. summation method adequate for predicting the discomfort caused by complex multi-axis motions?

Chapter 6 Predicting discomfort caused by fore-and-aft, lateral, and vertical whole-body vibration of seated passengers.

6.1 Introduction

The first of the two questions stemming from Chapter 5 is: does the rate-of-growth of discomfort differ between axes of vibration and, if so, is this sufficient to affect the inter-axis equivalence of discomfort between the axes?

For the prediction of the discomfort caused by the whole-body vibration of seated people, British Standard 6841 (1987) and International Standard 2631-1 (1997) suggest the vibration should be evaluated at three locations: on the supporting surface of the seat (in all six directions: fore-and-aft, lateral, vertical, roll, pitch, and yaw) and at the backrest and the feet (in all three translational directions: fore-and-aft, lateral, vertical). These vibrations are 'evaluated' by the root-mean-square (r.m.s.) or vibration dose value (VDV) after they have been weighted by frequency weightings assumed to reflect the frequency-dependence of the discomfort caused by vibration in each direction at each location.

Many experimental studies have investigated how the vibration discomfort of seated people depends on the frequency of vertical seat vibration (e.g., Griffin et al., 1982a, 1982b; Corbridge and Griffin, 1986; Morioka and Griffin, 2006a; Zhou and Griffin, 2014), the frequency of horizontal seat vibration (e.g., Griffin et al., 1982a, 1982b; Corbridge and Griffin, 1986; Morioka and Griffin, 2006a), the frequency of rotational seat vibration (e.g., Parsons and Griffin, 1982; Beard and Griffin, 2013), the frequency of vibration of the back (e.g., Parsons et al., 1982; Morioka and Griffin, 2010a; Basri and Griffin, 2011b) or the frequency of vibration of the feet (e.g., Parsons et al., 1982; Morioka and Griffin, 2010b). Although the frequency weightings in the current standards are broadly consistent with the experimental findings available in the 1980s and 1990s, complications have become apparent due to the influence of relative motion between seat and feet (e.g., Jang and Griffin, 2000), the inclination of backrests (e.g., Basri and Griffin, 2013), effects of low frequency rotation (e.g., Beard and Griffin, 2014), and the effects of mechanical shocks (e.g., Zhou and Griffin, 2017).

Research subsequent to the publication of the standards has also uncovered nonlinearities in subjective responses to vibration that indicate the frequency-dependence of vibration discomfort changes with the magnitude of vibration. The nonlinearity can be understood via Stevens' power law that relates the subjective magnitude, ψ, of a stimulus (e.g., the vibration discomfort) to the physical magnitude, φ, of the stimulus (e.g., the vibration acceleration) by:

$$\psi = k\varphi^n \tag{6.1}$$

where the exponent n represents the rate of growth of vibration discomfort as the physical magnitude of a vibration increases. It is becoming apparent that the rate of growth of discomfort, n, is not the same at all frequencies of vibration, or with all directions of vibration, or all locations of input of vibration to the body (see, for example, Morioka and Griffin, 2006a, 2010a,b; Wyllie and Griffin, 2007, 2009). This means that a vibration (with a specific frequency, direction, and location) can cause less discomfort than another vibration (with a different frequency, direction, or location) at low magnitudes but more vibration discomfort when the magnitudes of both vibrations are increased by the same percentage. This is not predicted by the frequency weightings in any current standard.

A potential explanation for the rate of growth of discomfort varying with the frequency and direction of vibration is that different frequencies and directions of vibration cause discomfort in different parts of the body. Perhaps increases in the magnitude of vibration cause a greater increase in discomfort at some locations in the body than at other locations in the body. As with the experiment reported in Chapter 2, a flat rigid seat will be utilised for this experiment. However it is anticipated that this may influence the location of greatest discomfort to the ischial tuberosities due to the high pressure experienced at the ischial tuberosities when sitting on a rigid flat seat. To determine whether or not this increased pressure has an effect on the location of discomfort, the experiment will be run both on a flat rigid seat and with participants sitting with a 'bean bag' underneath them to distribute the pressure more evenly whilst sitting. The 'bean bag' had a rigid response over the frequencies investigated in this study.

The weightings in British Standard 6841 (1987) and International Standard 2631 (1997) were influenced by experimental studies that gave the frequency-dependence of vibration discomfort with moderate magnitudes of vibration that might be commonly expected in some forms of transport (equivalent to the discomfort caused by 0.8 ms^{-2} r.m.s. vertical sinusoidal vibration at 10 Hz; Griffin et al., 1982b). Subsequent studies have reported a magnitude-dependence in vibration discomfort, but no study has explored how equivalent comfort contours in all three translational axes depend on the magnitude of vibration over the frequency range 1.0 to 10 Hz, even though these motions are often the dominant causes of vibration discomfort.

This chapter reports an experimental study of the frequency-dependence of the rate-of-growth of vibration discomfort, the magnitude-dependence of equivalent comfort contours, and how the location of greatest vibration discomfort depends on the frequency and direction of fore-and-aft, lateral, and vertical vibration of seated people. It was hypothesised that the rate of growth of discomfort would vary with the frequency of vibration and the direction of vibration. Due to these differences in the rate of growth of discomfort, equivalent comfort contours were expected to change shape with changes in the magnitude of vibration. It was also hypothesised that the location of greatest vibration discomfort would vary with the frequency, direction, and the magnitude of vibration and the distribution of pressure over the seat surface.

6.2 Method

6.2.1 Participants

Twenty-four subjects, twelve males and twelve females, who were students or office workers at the University of Southampton participated in the study. The male participants had a median age of 29 years (range 21 to 40 y), stature 1.82 m (range 1.63 to 1.94 m), and weight 75 kg (65 to 130 kg). The female participants had a median age of 29 years (range 19 to 38 y), stature 1.63 m (range 1.53 to 1.75 m), and weight 61 kg (45 to 78 kg). The physical characteristics of each subject are reported in Table 6.1.

The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (application number 19695).

6.2.2 Motions

Acceleration stimuli at the eleven preferred one-third octave centre frequencies from 1.0 to 10 Hz were generated using MATLAB (version 2012a) and HVLab toolbox (version 2). The transient stimuli (sinusoids modulated by a half sine) had n+0.5 cycles of oscillation (where n is an odd number adjusted to give durations of approximately 5.5 seconds). This number of cycles allowed the signal to start and finish with zero displacement, zero velocity, and zero acceleration. An example stimulus is shown in Figure 6.1.

Table 6.1 Participant characteristics.

Subject	Gender	Age (y)	Height (m)	Weight (kg)
1	F	19	1.75	65
2	M	21	1.83	73
3	M	23	1.83	77
4	M	29	1.82	77
5	F	29	1.58	54
6	M	26	1.65	75
7	M	29	1.85	96
8	M	29	1.88	130
9	M	31	1.70	67
10	M	32	1.72	65
11	M	24	1.83	75
12	F	34	1.63	65
13	M	25	1.71	73
14	F	32	1.53	45
15	F	29	1.55	66
16	F	31	1.73	53
17	F	25	1.63	78
18	F	27	1.62	72
19	M	40	1.78	75
20	F	30	1.53	55
21	F	22	1.58	57
22	F	38	1.70	69
23	M	24	1.94	86
24	F	31	1.66	53

Each frequency of motion was presented at seven magnitudes with increments of 3 dB. At each frequency and in each of the three directions of motion (fore-and-aft, lateral, and vertical) the frequency-weighted magnitudes were 0.088, 0.125, 0.175, 0.25, 0.35, 0.50, and 0.70 $m.s^{-2}$ r.m.s.

These magnitudes were frequency-weighted so as to maintain a reasonable range of discomfort across the 11 frequencies and three directions of motion. The frequency weightings used were those in British Standard 6841:1987 (i.e., W_b for vertical vibration and W_d for fore-and-aft and lateral vibration, with a unity axis multiplier in each direction). The unweighted vibration magnitudes are shown in Table 6.2.

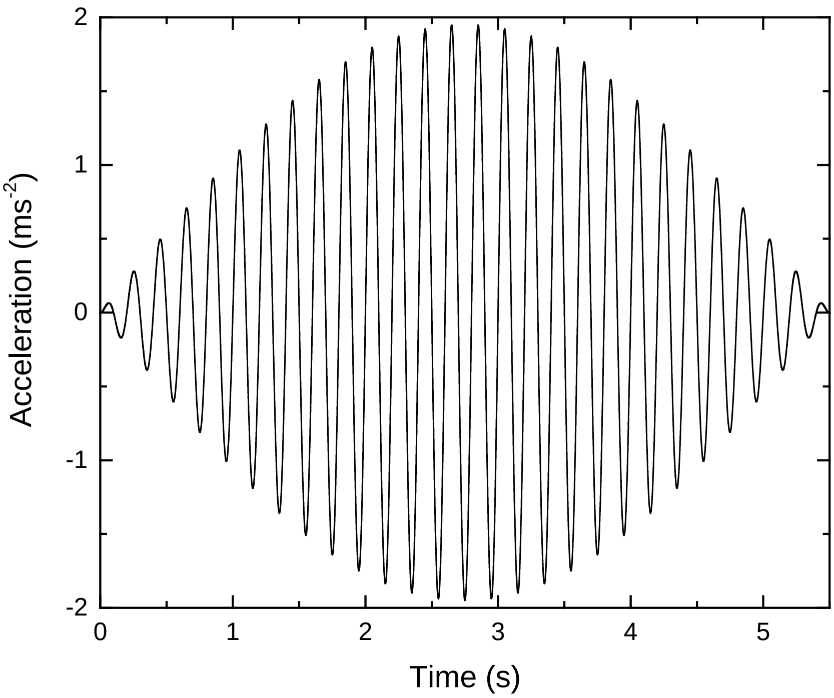

Figure 6.1 Example stimulus, one-octave bandwidth of vertical vibration centred on 2.0 Hz.

6.2.3 Apparatus

Fore-and-aft, lateral, and vertical random vibration was produced by the six-axis vibration simulator in the Institute of Sound and Vibration Research at the University of Southampton (Figure 6.2).

Subjects sat on a rigid seat (height: 0.56 m, width 0.50 m, and depth 0.50 m) with no backrest. They were supported either on the hard flat horizontal surface of the seat or on a ‘bean bag’ that distributed pressure over a larger area surrounding their ischial tuberosities. The ‘bean bag’ (height: 0.065 m, width: 0.41 m and depth 0.45 m) was filled with small rigid plastic pellets and had a transmissibility of unity in all three axes over the range of frequencies investigated. The feet of the subjects were supported on the vibrating platform using a rigid horizontal footrest that was adjusted in height so that the lower surfaces of the thighs were in contact with the seat or the beanbag.

Table 6.2 Unweighted acceleration magnitudes used in the study (m.s^{-2} r.m.s.).

Fore-and-aft											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
Magnitude 1	0.09	0.09	0.09	0.10	0.11	0.14	0.17	0.21	0.27	0.35	0.43
Magnitude 2	0.12	0.13	0.13	0.14	0.16	0.20	0.24	0.31	0.39	0.49	0.62
Magnitude 3	0.17	0.17	0.18	0.20	0.23	0.27	0.34	0.43	0.54	0.69	0.87
Magnitude 4	0.25	0.25	0.26	0.28	0.32	0.39	0.49	0.61	0.77	0.99	1.24
Magnitude 5	0.35	0.35	0.36	0.39	0.45	0.55	0.68	0.86	1.08	1.38	1.74
Magnitude 6	0.50	0.50	0.52	0.56	0.64	0.78	0.98	1.22	1.55	1.98	2.48
Magnitude 7	0.69	0.70	0.72	0.79	0.90	1.09	1.37	1.71	2.17	2.77	3.48
Lateral											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
Magnitude 1	0.09	0.09	0.09	0.10	0.11	0.14	0.17	0.21	0.27	0.35	0.43
Magnitude 2	0.12	0.13	0.13	0.14	0.16	0.20	0.24	0.31	0.39	0.49	0.62
Magnitude 3	0.17	0.17	0.18	0.20	0.23	0.27	0.34	0.43	0.54	0.69	0.87
Magnitude 4	0.25	0.25	0.26	0.28	0.32	0.39	0.49	0.61	0.77	0.99	1.24
Magnitude 5	0.35	0.35	0.36	0.39	0.45	0.55	0.68	0.86	1.08	1.38	1.74
Magnitude 6	0.50	0.50	0.52	0.56	0.64	0.78	0.98	1.22	1.55	1.98	2.48
Magnitude 7	0.69	0.70	0.72	0.79	0.90	1.09	1.37	1.71	2.17	2.77	3.48
Vertical											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
Magnitude 1	0.23	0.23	0.22	0.21	0.18	0.13	0.10	0.09	0.08	0.09	0.09
Magnitude 2	0.33	0.32	0.32	0.30	0.25	0.19	0.14	0.12	0.12	0.12	0.13
Magnitude 3	0.46	0.45	0.45	0.42	0.35	0.26	0.20	0.17	0.17	0.17	0.18
Magnitude 4	0.65	0.65	0.64	0.60	0.51	0.38	0.28	0.24	0.24	0.24	0.26
Magnitude 5	0.91	0.91	0.89	0.84	0.71	0.53	0.39	0.34	0.33	0.34	0.36
Magnitude 6	1.30	1.29	1.27	1.20	1.01	0.76	0.56	0.49	0.47	0.49	0.51
Magnitude 7	1.82	1.81	1.78	1.67	1.42	1.06	0.79	0.68	0.66	0.68	0.72

Figure 6.2 Experimental setup on the 6-axis vibration simulator.

6.2.4 Procedure

All subjects participated in two sessions on two separate days. The sessions lasted about 90 minutes with the same vibration stimuli and differed only in whether the 'bean bag' was placed on top of the rigid flat seat. With both seating conditions, all 231 stimuli were presented to each subject in an independently randomised order (between magnitude, frequency, and direction).

Subjects sat in comfortably upright postures on the rigid seat and were asked to remain upright throughout the experiment with their eyes shut to eliminate visual cues. They were monitored by the experimenter to ensure they followed these instructions. Participants wore headphones delivering white noise at 65 dB(A) to mask sounds produced by the simulator, which were less than 51 dB(A) at the subjects' ears.

During each session, the subjects were given time to read the instructions, sign consent and health questionnaire forms, practice magnitude estimation by judging the lengths of lines and judging the discomfort caused by a few example vertical vibrations (to ensure they understood the magnitude estimation method), and then participate in the experiment.

The method of magnitude estimation was used by subjects to rate the vibration discomfort they experienced during each motion. At the beginning and the end of their practice with vertical vibration, the subjects received 0.25 ms^{-2} at 3.15 Hz (frequency–weighted) and were instructed that the discomfort they experienced should be rated as '100' and used as a starting point for all their subsequent judgements. This ensured they used 'convenient' numbers throughout the experiment. The written instructions explained that a rating of 50 would mean their vibration discomfort was half that caused by a motion judged as having a discomfort of 100, and that a rating of 200 would mean that their vibration discomfort was double that caused by a motion having a discomfort of 100.

After each motion, subjects were asked to indicate the body location where the vibration was most felt in the body using a body map. The 12 body locations (numbered from 0 to 11) were: 0: 'no discernible location'; 1: head; 2: neck; 3: shoulders; 4: chest; 5: arms; 6: lower abdomen; 7: ischial tuberosities, 8: lower thighs; 9: upper thighs; 10: legs; and 11: feet.

6.2.5 Data analysis

For each frequency and direction of motion and every subject, the rate of growth of discomfort, *n*, and the constant, *k*, were determined by linear regression after a logarithmic transformation of Equation 6.1:

$$\log_{10} \psi = n \log_{10} \varphi + \log_{10} k \tag{6.2}$$

Prior to the linear regressions, magnitude estimates from individual subjects were normalised to give a median value of 100 within a session, so data from different subjects could be combined to produce median equivalent comfort contours. The normalisation does not affect the rate of growth of discomfort, *n*, only the intercept, *k*.

Equivalent comfort contours for selected levels of vibration discomfort (corresponding to magnitude estimates of 63, 80, 100, 125, and 160) were calculated using:

$$\varphi = 10^{((\log_{10} \psi) - (\log_{10} k)/n)} \tag{6.3}$$

where φ is unweighted acceleration in ms^{-2}.

6.2.6 Statistical tests

The data were analysed using non-parametric statistics in SPSS (version 22). The Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks indicated differences between related samples. The Mann-Whitney U test was used for differences between independent samples. The Cochran-Q test was used to investigate differences in body locations associated with greatest discomfort for related samples and the McNemar change test was used to investigate changes in body location between magnitudes.

6.3 Results

The median rates of growth, *n*, and the constants, *k*, for each frequency of vibration in each of the three axes of vibration when sitting on the rigid seat are shown in Table 6.3.

Table 6.3 Median exponents, *n*, and constants, *k*, for each of the three axes for the rigid seat.

Frequency (Hz)	Fore-and-aft		Lateral		Vertical	
	k	*n*	*k*	n	*k*	*n*
1.0	189	0.54	165	0.53	107	0.87
1.25	160	0.42	180	0.63	109	0.75
1.6	163	0.57	241	0.76	104	0.69
2.0	178	0.62	194	0.60	107	0.69
2.5	182	0.68	177	0.48	113	0.68
3.15	172	0.51	140	0.37	133	0.72
4.0	148	0.36	137	0.39	191	0.70
5.0	131	0.34	117	0.38	187	0.69
6.3	112	0.41	114	0.31	167	0.45
8.0	107	0.30	110	0.28	210	0.67
10.0	101	0.36	111	0.32	188	0.59

6.3.1 Rate of growth of discomfort

6.3.1.1 Within directions of vibration

Within each of the three directions of vibration, and with both seating conditions, the rate of growth of vibration discomfort, *n*, was highly dependent on the frequency of the vibration ($p<0.001$; Friedman; Figure 6.3). Over the frequency range 1 to 10 Hz, the percentage change in the rate of growth of discomfort was less with vertical vibration than with either fore-and-aft or lateral vibration.

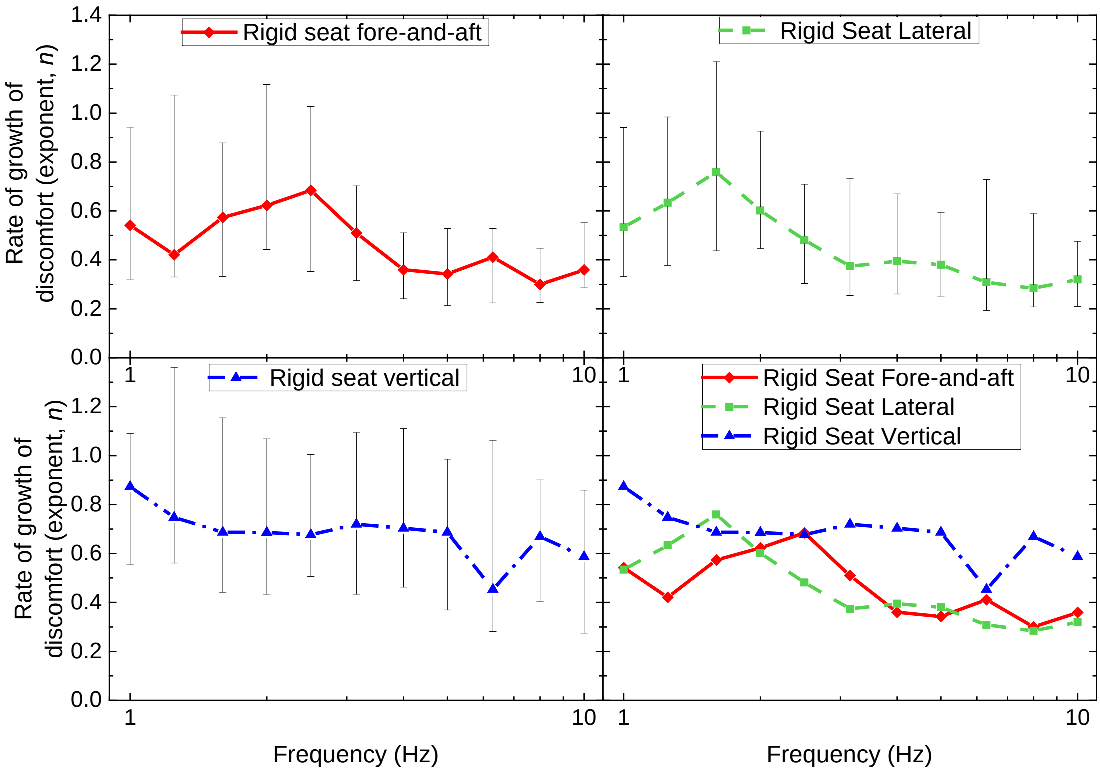

Figure 6.3 Rates of growth of vibration discomfort, *n*, for fore-and-aft vibration (top left), lateral vibration (top right), and vertical vibration (bottom left), and all three directions of vibration (bottom right) when sitting on a rigid seat without a backrest. Medians and inter-quartile ranges for 24 subjects.

6.3.1.2 Between directions of vibration

At all eleven frequencies, and with both seating conditions, the rate of growth of vibration discomfort differed across the three directions of vibration ($p<0.05$, Friedman).

Without the beanbag, there was no statistically significant difference in the rate of growth of vibration discomfort between fore-and-aft and lateral vibration ($p>0.05$, Wilcoxon), except at 1.6 Hz and 2.5 Hz ($p=0.004$ and $p=0.002$, respectively, Wilcoxon). With the beanbag, there was no statistically significant difference in the rate of growth between fore-and-aft and lateral vibration ($p>0.05$, Wilcoxon), except at 4 Hz and 5 Hz ($p=0.022$ and $p=0.005$, respectively, Wilcoxon).

Without the beanbag, the rate of growth of vibration discomfort was significantly greater with vertical vibration than with either fore-and-aft or lateral vibration ($p<0.02$, Wilcoxon; Figure 6.3), except between vertical and fore-and-aft vibration from 1.6 to 2.5 Hz and between vertical and lateral vibration from 1.6 to 2.0 Hz (Figure 6.3). With the beanbag, the rate of growth of vibration discomfort was also significantly greater with vertical vibration than with either fore-and-aft or lateral vibration ($p<0.04$, Wilcoxon), except between vertical and fore-and-aft vibration at 1.25 Hz and from 2.0 to 2.5 Hz and between vertical and lateral vibration from 1.25 to 2.0 Hz, and at 6.3 Hz and 10 Hz.

6.3.1.3 Between seating conditions

Over all 11 frequencies and the three directions of vibration, the rate of growth of vibration discomfort was not significantly affected by whether subjects sat with or without the beanbag ($p>0.05$, Wilcoxon; Figure 6.4), except with fore-and-aft vibration at 10 Hz ($p=0.012$, Wilcoxon) and with vertical vibration at 1.25 and 8 Hz ($p=0.024$ and 0.021, respectively, Wilcoxon). With 33 comparisons, these three differences could be considered the result of chance.

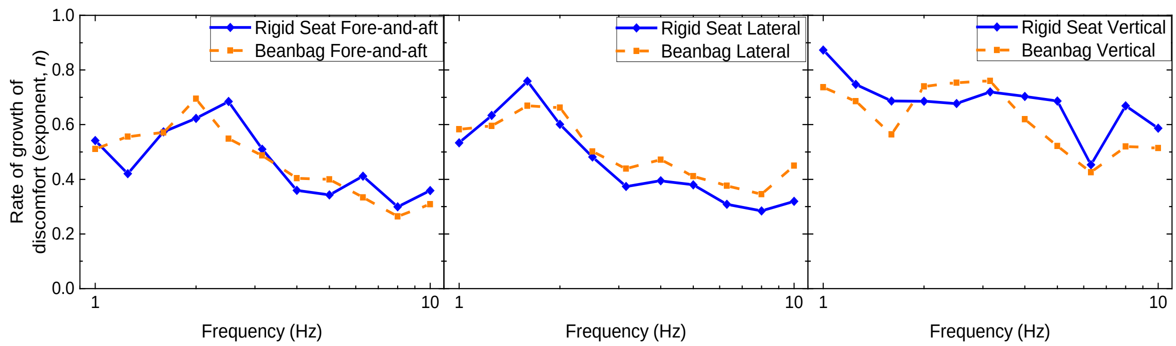

Figure 6.4 Rates of growth of vibration discomfort, *n*, for fore-and-aft vibration (left), lateral vibration (centre), and vertical vibration (right) when sitting without a backrest on either a rigid seat or a beanbag. Median values for 24 subjects.

6.3.2 Equivalent comfort contours

6.3.2.1 Within directions of vibration

Equivalent comfort contours were determined by calculating values of the vibration acceleration, φ, corresponding to five subjective magnitude, ψ: 63, 80, 100, 125, and 160 (where ψ = 100 is equivalent to the discomfort caused by 3.15-Hz vertical vibration at 0.25 ms^{-2} r.m.s., weighted, 0.38ms^{-2}, unweighted).

In all three directions and at all five subjective magnitudes, the levels of the equivalent comfort contours were highly dependent on the frequency of vibration ($p<0.001$, Friedman). With all three directions of vibration, the discomfort caused by acceleration was almost independent of the frequency of vibration at frequencies less than about 2 or 3 Hz. As the frequency increased to 10 Hz, the vibration magnitude required to produce the same degree of discomfort progressively increased for the two directions of horizontal vibration but decreased for vertical vibration.

With less percentage change in the rate of growth of discomfort with vertical vibration, the equivalent comfort contours for vertical vibration were less affected by the magnitude of the vibration than the equivalent comfort contours for horizontal vibration. Nevertheless, with all three directions of vibration, the greater rate of growth of discomfort at lower frequencies caused closer equivalent comfort contours: less change in the magnitude of vertical vibration was needed with the lower frequencies to produce the same change in vibration discomfort. The rate of growth of discomfort was generally greater with vertical vibration, so less change in magnitude was needed with vertical vibration than with horizontal vibration to produce the same change in discomfort.

6.3.2.2 Between directions of vibration

Equivalent comfort contours for fore-and-aft, lateral, and vertical acceleration are compared for subjective magnitudes of 63, 80, 100, 125, and 160 in Figure 6.5.

With all five subjective magnitudes, there was significantly greater sensitivity to lateral vibration than to fore-and-aft vibration at 1.6 and 2.0 Hz ($p<0.02$, Wilcoxon) and with subjective magnitudes of 63 and 80 at 2.5 Hz ($p<0.02$, Wilcoxon). There was significantly greater sensitivity to fore-and-aft vibration than to lateral vibration with all subjective magnitudes at 4.0 Hz ($p<0.05$, Wilcoxon), and at 3.15 Hz with subjective magnitudes of 100 and greater ($p<0.01$, Wilcoxon).

Previous research has suggested a ‘crossover’ between sensitivity to vertical vibration and horizontal vibration at 3.15 Hz, with fore-and-aft and lateral vibration giving more discomfort at frequencies less than 3.15 Hz and vertical vibration giving more discomfort at frequencies greater than 3.15 Hz (Griffin and Whitham, 1977; Fairley and Griffin, 1988). In this study, the frequency of the crossover between fore-and-aft vibration and vertical vibration decreased with increasing magnitude of vibration (Figure 6.6). With a subjective magnitude of 63 (without the beanbag), the crossover frequency was between 5 and 6.3 Hz: subjects were more sensitive to fore-and-aft vibration than to vertical vibration at all frequencies less than 5 Hz ($p<0.001$, Wilcoxon) and more sensitive to vertical vibration than to fore-and-aft vibration at frequencies greater than 6.3 Hz ($p<0.05$, Wilcoxon). With subjective magnitudes of 80 and 100, the frequency at which there was no significant difference between sensitivity to fore-and-aft and vertical vibration was 5 Hz. With subjective magnitudes of 125 and 160, the frequency at which there was no significant difference reduced to 4 Hz.

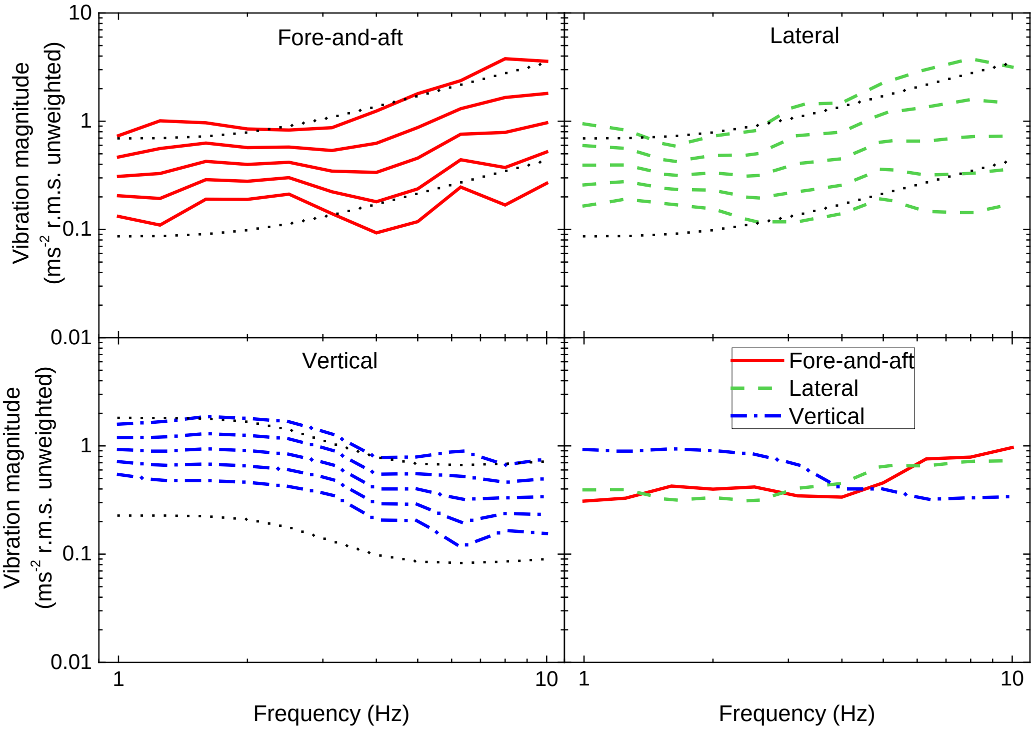

Figure 6.5 Equivalent comfort contours for fore-and-aft, lateral and vertical vibration for subjective magnitudes from 63 to 160 relative to 0.25 ms^{-2} vertical vibration at 3.15 Hz. Ranges of stimuli employed in the study shown by dotted lines (….). Bottom right compares equivalent comfort contours between the three directions for a subjective magnitude of 100.

With increasing magnitude of vibration, there was a similar reduction in the frequency of the crossover in sensitivity between lateral vibration and vertical vibration (Figure 6.6). With a subjective magnitude of 63, the crossover frequency was at 5 Hz: subjects were more sensitive to lateral vibration at all frequencies less than 5 Hz (p<0.005, Wilcoxon) and more sensitive to vertical vibration at all frequencies greater than 5 Hz (p<0.05, Wilcoxon), except at 10 Hz (p=0.219). With a subjective magnitude of 80, subjects were more sensitive to lateral vibration at 5 Hz and lower frequencies and more sensitive to vertical vibration at 6.3 Hz and higher frequencies, with significant differences at all frequencies (p<0.05). For a subjective magnitude of 100, the frequency at which there was no significant difference was 4 Hz. For a subjective magnitude of 125, subjects were more sensitive to lateral vibration at 3.15 Hz and lower frequencies and more sensitive to vertical vibration at 4 Hz and higher frequencies, with significant differences at all frequencies (p<0.05). With a magnitude estimate of 160, the frequency at which there was no significant difference reduced to 3.15 Hz.

There were similar trends in relative sensitivity to vibration in the three axes when subjects sat on the beanbag.

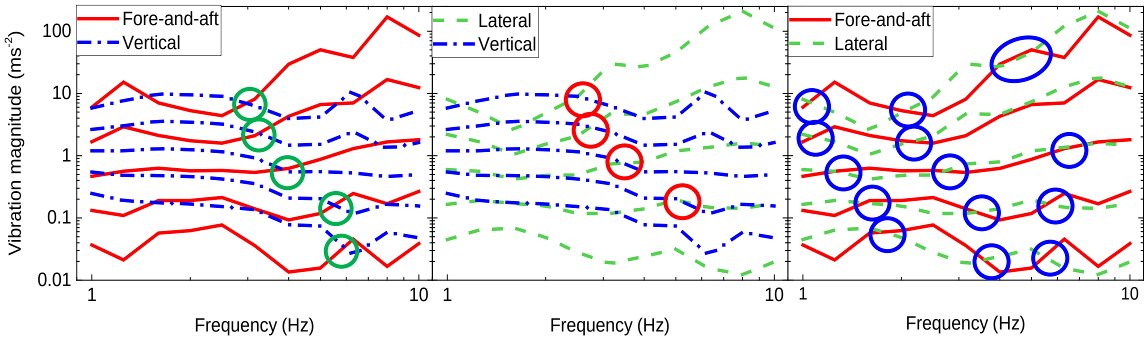

Figure 6.6 Comparisons of equivalent comfort contours between axes for subjective magnitudes from 63 to 160 in the fore-and-aft (red), lateral (green) and vertical (blue) directions, relative to a vibration magnitude of 0.25 ms^{-2} vertical vibration at 3.15 Hz. Without beanbag. Circles show systematic changes in the frequencies of the cross-overs between pairs of equivalent comfort contours in different axes. Median data from 24 subjects.

6.3.3 Between seating conditions

Subjects judged discomfort with and without the beanbag cushion on separate days, so magnitude estimates of discomfort do not directly indicate whether there were any overall differences in vibration discomfort between the two seating conditions. However, the frequency-dependence of discomfort and the direction-dependence of discomfort can be compared between the two seating conditions.

The variable '*k*' in equation 1 reflects the frequency-dependence and direction-dependence of subject estimates of vibration discomfort. For example, irrespective of the rate of growth of vibration discomfort (i.e., *n)*, the value of *k* gives the subjective magnitude, ψ, when the vibration magnitude is 1.0 ms^{-2} r.m.s. If changes to the distribution of force between the beanbag and the subjects affected the frequency-dependence or direction-dependence of discomfort caused by vibration, the ratio of the value of *k* with and without the beanbag would vary with the frequency or the direction of vibration.

Over the 11 frequencies within each of the three directions of vibration, the ratio of the value of *k* with and without the beanbag varied over the range to 0.83 to 1.27. After adjusting for 11 multiple comparisons within each direction, the ratio was only statistically significant with 5-Hz lateral vibration where the ratio was 0.83 (p = 0.01). For this combination of frequency and direction, the finding suggests subjects were more sensitive to lateral vibration when sitting on the beanbag. However, this finding could be due to chance and it is noted that the ratio was close to 1.0 at adjacent frequencies.

The effect of the beanbag on the direction-dependence of vibration discomfort was investigated at each frequency by comparing the ratio of *k*-values between sitting with and without the beanbag between all three possible pairs of directions. These ratios varied between 0.73 and 1.22. After adjusting for multiple comparisons, none of the ratios showed a statistically significant effect of the beanbag. It is concluded that the direction-dependence of vibration discomfort was not affected by the beanbag at any of the 11 frequencies.

6.3.4 Body location

The principal locations of discomfort identified by subjects when sitting on the rigid seat during exposure to fore-and-aft, lateral, and vertical vibration at 'low' magnitudes (0.088 ms^{-2} r.m.s., weighted) and 'high' magnitudes ((0.70 ms^{-2} r.m.s., weighted) are shown in Figure 6.7. The corresponding locations when sitting on the beanbag are shown in Figure 6.8.

6.3.4.1 Effect of frequency of vibration

With fore-and-aft vibration, the areas of the body in contact with vibration (the ischial tuberosities and lower thighs) became progressively more dominant locations of discomfort as the frequency of low magnitude vibration increased from 1.0 to 10 Hz in both seating conditions ($p<0.01$, Cochran Q). There was a corresponding statistically significant reduction in the dominance of vibration discomfort in the lower and upper torso as the frequency of fore-and-aft high magnitude vibration increased from 1 to 10 Hz ($p<0.02$, Cochran Q).

with both seating conditions ($p<0.01$, Cochran Q). There was a corresponding reduction in the discomfort experienced at the head as the frequency increased ($p<0.05$, Cochran Q) with no reports of discomfort at the head with frequencies greater than 3.15 Hz.

With high magnitude vertical vibration without the beanbag, the head, neck and shoulders were dominant sources of discomfort at lower frequencies (1 to 4 Hz) but not at higher frequencies ($p<0.001$, Cochran Q).

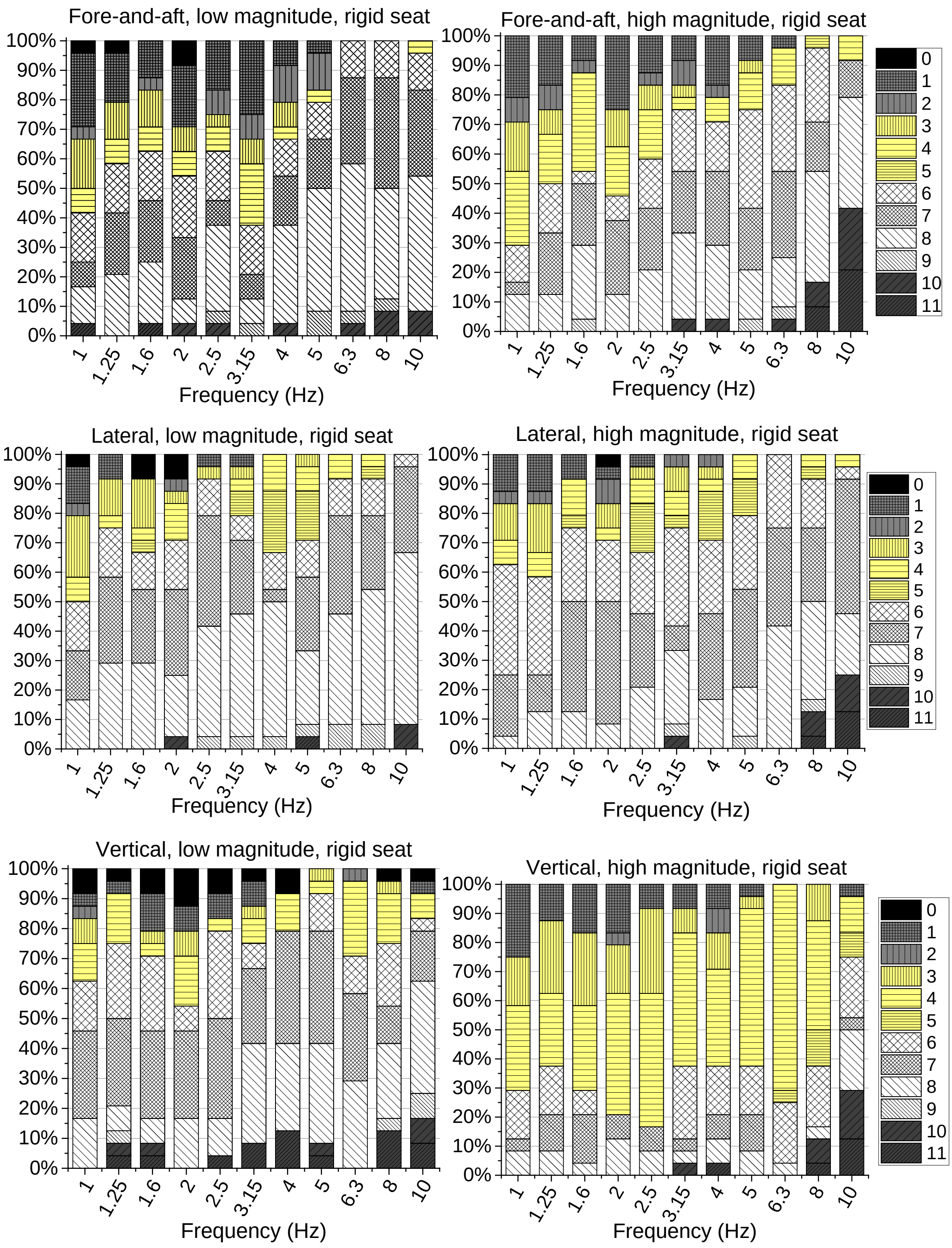

Figure 6.7 Reported body locations of most discomfort in each axis of vibration, at 'low' magnitudes (0.088 ms^{-2} r.m.s., weighted) and 'high' magnitudes (0.70 ms^{-2} r.m.s., weighted) with a rigid seat. Body locations – 0: 'no discernible location'; 1: head; 2: neck; 3: shoulders; 4: chest; 5: arms; 6: lower abdomen; 7: ischial tuberosities, 8: lower thighs; 9: upper thighs; 10: legs; and 11: feet.

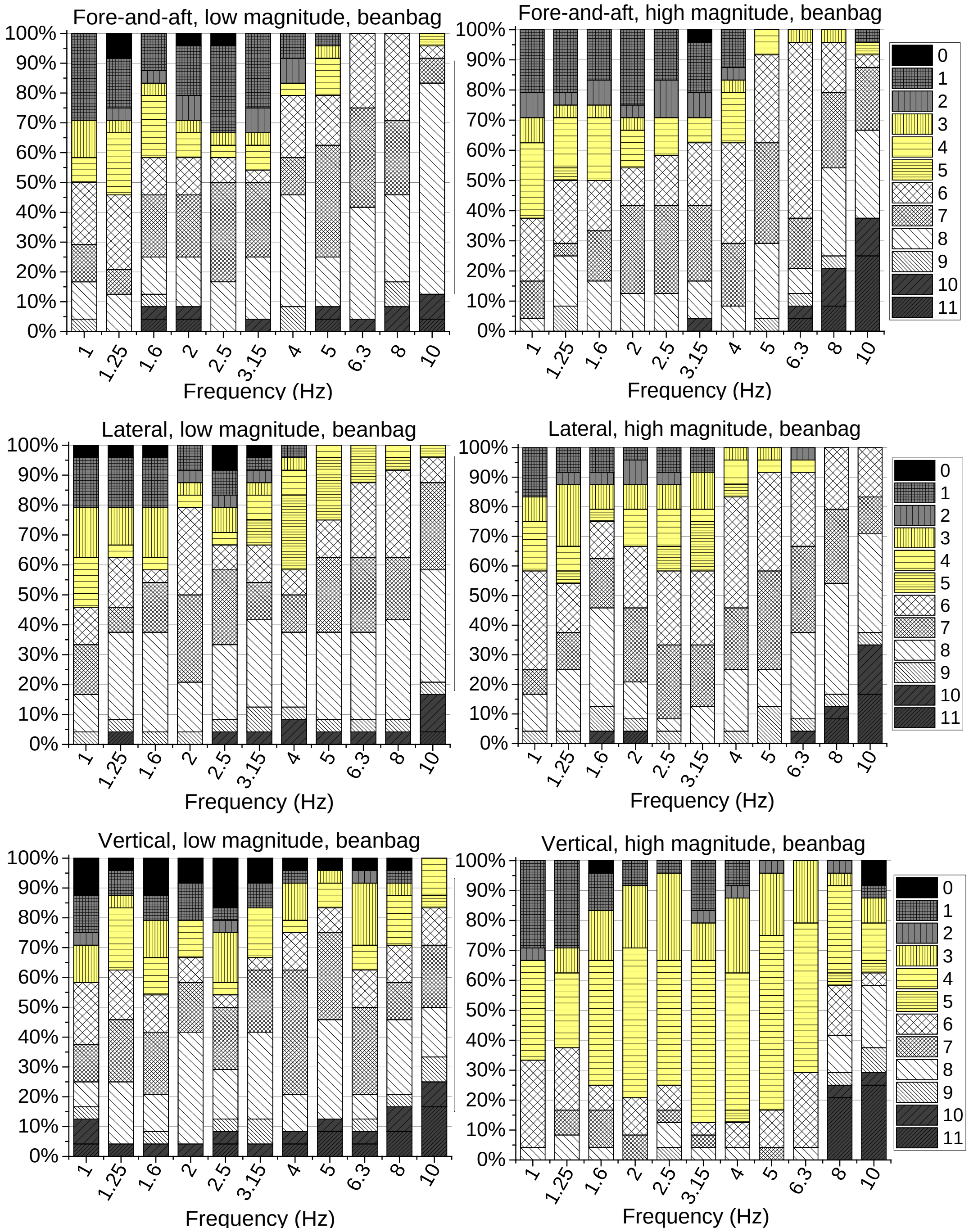

Figure 6.8 Reported body locations of most discomfort in each axis of vibration, at 'low' magnitudes (0.088 ms^{-2} r.m.s., weighted) and 'high' magnitudes (0.70 ms^{-2} r.m.s., weighted) when sitting on the beanbag. Body locations – 0: 'no discernible location'; 1: head; 2: neck; 3: shoulders; 4: chest; 5: arms; 6: lower abdomen; 7: ischial tuberosities, 8: lower thighs; 9: upper thighs; 10: legs; and 11: feet.

With lateral vibration, the areas of the body in contact with vibration also became more dominant locations of discomfort as the frequency of low magnitude vibration increased from 1.0 to 10 Hz

With the higher frequencies of vibration, the legs and feet were frequently identified as dominant locations of discomfort, particularly with higher magnitudes of vibration, but in no condition were the feet and lower legs identified as the location of greatest discomfort by the majority of subjects.

6.3.4.2 **Effect of magnitude of vibration**

Increases in the magnitude of vertical vibration caused a large increase in reports of dominant discomfort in the chest and shoulders, and reduced reports of dominant discomfort around the ischial tuberosities and lower thighs (Figures 6.7 and 6.8). For the purposes of statistical analysis, reports of dominant discomfort in the shoulders or chest were combined and reports of dominant discomfort at the ischial tuberosities or lower thighs were combined. With the rigid seat, when the vibration magnitude increased from ‘low’ to ‘high’, reports of dominant discomfort in the shoulders or chest were significantly increased at frequencies from 1.0 to 6.3 Hz and reports of dominant discomfort around the ischial tuberosities or lower thighs were reduced at 1.0 Hz and from 2.5 to 8 Hz (Table 6.4). With the beanbag, when the vibration magnitude increased from ‘low’ to ‘high’, reports of dominant discomfort in the shoulders or chest were significantly increased at frequencies from 1.6 to 6.3 Hz and reports of discomfort around the ischial tuberosities or lower thighs were reduced at 2.0 Hz and from 3.15 to 6.3 Hz (Table 6.4).

6.3.4.3 **Effect of beanbag**

The beanbag had little effect on the location of dominant discomfort with any of the three directions of vibration at any frequency (compare Figures 6.7 and 6.8). Contrary to expectations, the ischial tuberosities were not less dominant locations of discomfort when the beanbag distributed the pressure to a larger area (p>0.05, McNemar).

With fore-and-aft and lateral vibration, the range of magnitudes of vibration included in the study had no statistically significant effect on the location of discomfort at any frequency of vibration.

Table 6.4 The effect of magnitude of vertical vibration on the location of dominant discomfort (*p*-values; McNemar test): ↑ statistically significant increase in reports of discomfort at these locations with increasing magnitude of vibration; ↓ statistically significant decrease in reports of discomfort at these locations with increasing magnitude of vibration.

Rigid seat, locations 3 or 4 (shoulders or chest)

1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
0.031↑	0.021↑	0.001↑	0.021↑	0.000↑	0.006↑	0.008↑	0.000↑	0.001↑	0.092	1.000

Rigid seat, locations 7 or 8 (ischial tuberosities or lower thighs)

1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
0.008↓	0.344	0.219	0.070	0.016↓	0.002↓	0.002↓	0.002↓	0.001↓	0.021↓	0.092

Beanbag seat, locations 3 or 4 (shoulders or chest)

1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
0.227	0.754	0.039↑	0.001↑	0.000↑	0.000↑	0.000↑	0.000↑	0.006↑	0.453	0.687

Beanbag seat, locations 7 or 8 (ischial tuberosities or lower thighs)

1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
0.219	0.146	0.289	0.007↓	0.146	0.002↓	0.000↓	0.000↓	0.008↓	0.070	0.388

6.4 Discussion

6.4.1 Rate of growth of discomfort

The rate of growth of vibration discomfort varied over the frequency range (1.0 to 10 Hz) within all three axes of vibration (fore-and-aft, lateral, and vertical) and differed between these axes of vibration. This means that the shapes of the equivalent comfort contours (and corresponding frequency weightings) will change with changing magnitude of vibration and the relative discomfort caused by vibration in each axis will change as the magnitude of vibration changes.

A vibration with a greater rate of growth of vibration discomfort becomes a more important source of discomfort as the vibration magnitudes increase. Referring to Figure 6.3, as the magnitudes of horizontal vibration increase, fore-and-aft vibration around 2.5 Hz and lateral vibration around 1.6 Hz will become more important sources of vibration discomfort. Relative to horizontal vibration, vertical vibration will increase in importance as a source of discomfort as the magnitude of vibration increases at frequencies greater than about 3 Hz.

The median rates of growth of discomfort found in this study varied over an approximately 2:1 range, from about 0.4 to 0.8. A vibration with a rate of growth of 0.4 must increase in magnitude by a factor of four to produce the percentage increase in vibration discomfort achieved by only doubling the magnitude of a vibration with a rate of growth of 0.8. The variations in the rate of growth of vibration discomfort over frequencies and directions can therefore have a large effect of the relative importance of different frequencies and directions of vibration in causing vibration discomfort.

There are various potential causes for a frequency-dependence and direction-dependence in the rate of growth of discomfort. The rate of growth is likely to depend on the location in the body where the vibration causes greatest discomfort, with increased discomfort in the upper torso (location 4) during higher magnitudes of vertical vibration partially explaining the greater rate of growth of discomfort with vertical vibration at frequencies greater than about 3 Hz. A similar explanation has been offered for differences in the rate of growth of discomfort between vertical vibration at the feet and vertical vibration at the seat (Jang and Griffin, 2000). Local peaks and troughs in the frequency-dependence of the rate of growth of vibration discomfort may arise from the biodynamic nonlinearities of the body that cause the frequency of greatest response to reduce as the vibration magnitude increases (Matsumoto and Griffin, 2005; Subashi *et al*., 2009).

The rate of growth of discomfort has varied between studies (Figure 6.9). Potential reasons for the variation between studies include different seats employed (flat or contoured), different footrest conditions (stationary or moving with the seat), the amount of thigh contact, and whether the subjects' eyes were open or closed. The current study tried to prevent secondary cue's from influencing subject judgements by requiring eyes to be closed and masking the noise from the vibrating platform. Future studies should investigate what factors apart from the frequency and magnitude of vibration influence the rate of growth of discomfort.

Over the frequency range 1.0 to 10 Hz, the rate of growth of vibration discomfort varies more for vibration in the horizontal directions than for vibration in the vertical direction. Among potential causes for this difference are the different mechanisms involved in producing sensations, including changes in the location of principal vibration discomfort with changing frequency and changing direction of vibration.

6.4.2 Equivalent comfort contours

6.4.2.1 Within directions of vibration

With both fore-and-aft and lateral vibration, the acceleration equivalent comfort contours show little dependence on the frequency of vibration at the lower magnitudes (around 0.1 to 0.2 ms^{-2} r.m.s.) but reduced sensitivity to the higher frequencies with greater magnitudes of vibration (Figure 6.5).

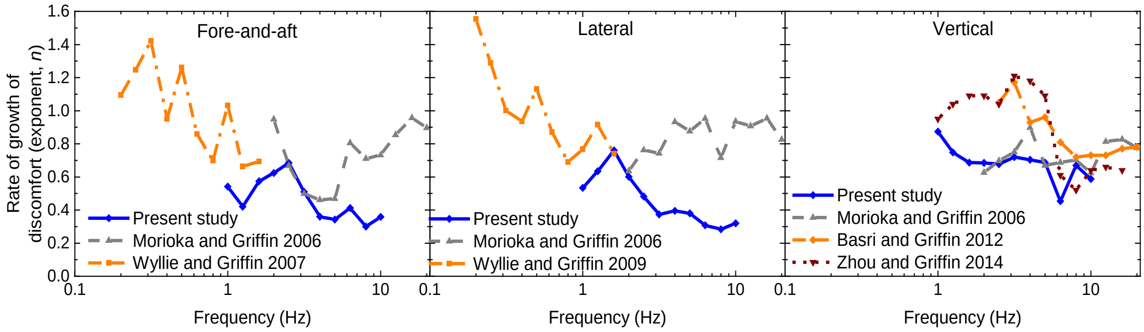

Figure 6.9 Rates of growth of vibration discomfort, *n*, for fore-and-aft, lateral and vertical whole-body vibration for a rigid seat without a backrest reported in various studies.

The frequencies of greatest vibration discomfort caused by fore-and-aft and lateral acceleration appear to reduce with increasing magnitude of vibration and occur at a higher frequency for fore-and-aft vibration than for lateral vibration, consistent with Subashi *et al.* (2009). With low magnitudes of vertical acceleration, vibration discomfort increases with increasing frequency up to about 6.3 Hz, whereas the increase occurs up to only about 4 or 5 Hz at the higher magnitudes, consistent with Matsumoto and Griffin (2005) and Zhou and Griffin (2014).

6.4.2.2 Between directions of vibration

The relative sensitivity to fore-and-aft and lateral vibration depends on the magnitude of vibration, but at the magnitudes used in this study there was greater sensitivity to lateral vibration around 1.6 to 2 Hz and greater sensitivity to fore-and-aft vibration around 3.15 to 4 Hz (Figure 6.6).

Currently, both BS 6841:1987 and ISO 2631-1:1997 indicate that unweighted vertical acceleration causes greater discomfort than unweighted horizontal vibration at frequencies greater than 3.15 Hz and less discomfort than unweighted horizontal vibration at frequencies less than 3.15 Hz. This study shows that the effect of vibration magnitude on the shapes of the equivalent comfort contours causes the frequency of the cross-over between sensitivity to vertical and horizontal vibration to change with the magnitude of vibration (Figure 6.6). At low magnitudes, the frequency of the cross-over was as high as 6.3 Hz, but this reduced with increasing magnitude of vibration and was not always the same for fore-and-aft and lateral vibration.

6.4.3 Body locations showing greatest discomfort

With fore-and-aft and lateral vibration, the location of greatest discomfort was at, or close to, the interface between the occupant and the seat (i.e., locations 6/7/8). The likely cause of the discomfort being located here is shearing between the seat surface and the occupant, and weak transmission of vibration through the body. Because of the shearing, less motion was transferred to the torso of the body and so the location of discomfort did not change much with a change in magnitude.

With vertical vibration at the lower magnitudes, the location of greatest discomfort was spread across all possible locations but with a tendency towards greatest discomfort at the interface with the seat surface. At the higher magnitudes of vertical vibration, the location of greatest discomfort moved towards the upper body. This suggests the rate of growth of discomfort differed between body areas, with lower rates of growth of discomfort in peripheral areas and higher rates of growth of discomfort in central areas of the body. Consequently, vibration discomfort was located predominantly in the central parts of the body with higher magnitudes of vertical vibration but distributed more uniformly with lower magnitudes of vertical vibration.

The locations of discomfort in the body caused by fore-and-aft, lateral, and vertical whole-body vibration when sitting on a flat rigid seat with feet supported on a stationary footrest have been investigated previously (Whitham and Griffin, 1978). With fore-and-aft and lateral vibration, the areas of most discomfort were in the area of the lower abdomen and the buttocks, with greatest discomfort at the ischial tuberosities. With vertical vibration in the range of 4 to 16 Hz, greatest discomfort was in the upper parts of the body, consistent with the current study. Whitham and Griffin used a vibration magnitude of 1.0 $m.s^{-2}$ (unweighted), so at frequencies less than 4 Hz the magnitude was close to the middle magnitude used in the current study. With 2-Hz vertical vibration, they found discomfort fairly evenly distributed over body locations, similar to the lower magnitudes of vibration in the current study.

In a study with vertical vibration and no backrest, middle magnitudes produced discomfort primarily in the buttocks and lower thighs at low frequencies (2.5 to 4.0 Hz) but, as the frequency increased above 5.0 Hz, there was increased discomfort in the lower and upper back, although the buttocks and the lower thighs remained the primary location of discomfort (Basri and Griffin, 2012). At the highest magnitude investigated, discomfort was mostly located at the buttocks at 2.5 and 3.15 Hz, with increasing discomfort at the lower back and upper back as the frequency increased to 6.3 Hz. Discomfort at the buttocks and lower thighs increased from 8.0 to 10 Hz. This is reasonably consistent with the current study where increasing the magnitude of vertical direction changed the location of greatest discomfort from the interfaces between the subject and the seat (ischial tuberosities and thighs) to more central parts of the body (lower abdomen and chest).

In a later study, at the higher magnitudes and at frequencies greater than 1.0 Hz, there was some discomfort in the head as well as in the central parts of the body (Basri and Griffin, 2013). As frequencies increased, the head became a less important location for discomfort in favour of the upper back and the lower back. At 8.0 and 10 Hz, the locations of greatest discomfort lowered to the buttocks and the lower thighs. This is also in reasonable agreement with the current study, which found some discomfort at the head decreasing with frequency increasing from 1.0 to 4.0 Hz, the chest becoming a greater location of discomfort with increasing frequency up to 6.3 Hz, and the lower abdomen, thighs, and legs becoming more uncomfortable at 8.0 and 10 Hz.

The location of greatest discomfort has also been found in the lower part of the body with lateral vibration and in the upper body with vertical vibration by Griefahn and Brode (1999).

6.4.4 Effect of beanbag

There were no systematic differences in the rates of growth of discomfort in any of the three directions between sitting with and without the beanbag. Similarly, there was little effect of the beanbag on the equivalent comfort contours.

Acceleration measured on the beanbag with a sit-pad indicated that it was rigid over the frequency range used in this study, so it is reasonable for it not to affect the rates of growth of discomfort or the equivalent comfort contours. However, prior to the experiment it was hypothesised that without the beanbag there would be more reports of the location of dominant discomfort at the ischial tuberosities, because of increased pressure around the ischial tuberosities. The absence of any large effect suggests that the findings from many previous studies with rigid flat seat surfaces are not restricted to only those seating conditions.

6.4.5 Implications for methods of evaluating whole-body vibration with respect to vibration discomfort

Similar to some previous studies (e.g., Morioka and Griffin, 2006a; Wyllie and Griffin, 2007, 2009; Basri and Griffin, 2012; Zhou and Griffin, 2014) this study found that the rate of growth of vibration discomfort depended on the frequency of vibration. There was a frequency-dependence of the rate of growth of vibration discomfort with fore-and-aft, lateral, and vertical whole-body vibration and, at each frequency, the rate of growth differed between the directions of vibration. This means the optimum frequency weightings for vibration discomfort, and the optimum multiplying factors to represent relative sensitivity to each direction of vibration depend on the magnitude of vibration.

The finding of different equivalent comfort contours for fore-and-aft and lateral vibration suggests it is inappropriate to evaluate vibration in these two directions using the same frequency weighting. However, the larger difference is between these contours and the standardised frequency weighting W_d (Figure 6.10). This weighting will tend to underestimate the discomfort caused by low magnitudes of higher frequencies of vibration, as reported previously by Morioka and Griffin (2006a), but it is more appropriate when predicting the discomfort of higher magnitudes of fore-and-aft or lateral vibration. So although there are consistent differences between the equivalent comfort contours for fore-and-aft and lateral vibration, the differences due to the change in the frequency-dependence with changing magnitude of vibration merit greater consideration.

For the conditions investigated here, the rate of growth of vibration discomfort is greater for all directions of vibration at low frequencies and generally greater with vertical vibration than horizontal vibration. Consequently, the shapes of equivalent comfort contours, and the equivalence between directions of vibration, change as the magnitude of vibration changes. These differences are not reflected in the standards that recommend the use of the same frequency weightings and the same axis multiplying factors for predicting the discomfort caused by all magnitudes of vibration.

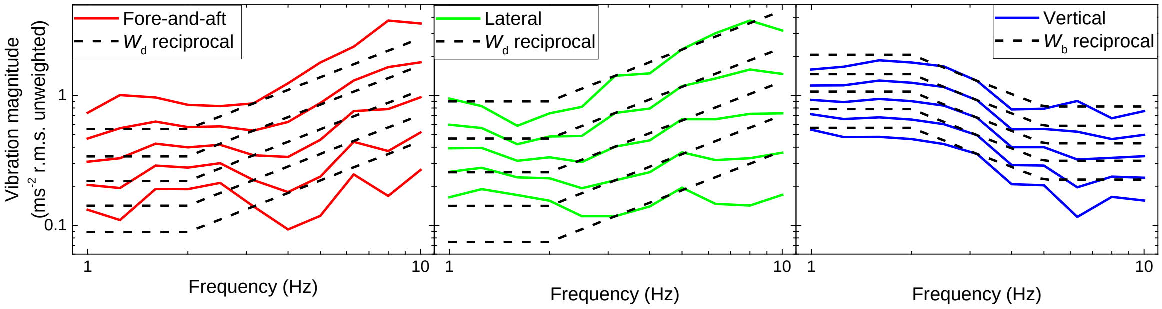

Figure 6.10 Equivalent comfort contours for subjective magnitudes from 63 to 160 in the fore-and-aft, lateral, and vertical directions, relative to 0.25 ms^{-2} r.m.s. vertical vibration at 3.15 Hz. Contours compared with the reciprocals of the asymptotic versions of frequency weightings W_d and W_b for horizontal and vertical vibration, respectively. The reciprocal weightings have been adjusted to be equal to the equivalent comfort contours at 3.15 Hz.

6.5 Conclusions

The rate-of-growth of vibration discomfort with increasing magnitude of fore-and-aft, lateral, or vertical vibration is highly dependent on the frequency of the vibration and depends on the direction of the vibration. Equivalent comfort contours therefore have a frequency-dependence that depends on the magnitude of vibration and the relative contributions of fore-and-aft, lateral, and vertical vibration to discomfort depend on the magnitude of vibration.

With all directions of vibration, but especially horizontal vibration (fore-and-aft and lateral), the frequency-dependence of the acceleration required to cause similar discomfort becomes more marked as the magnitude of vibration increases. At the higher magnitudes of vibration studied here, the frequency-dependence of discomfort is consistent with frequency weighting W_b (for vertical vibration) and frequency weighting W_d (for horizontal vibration), although there are systematic differences in the frequency-dependence of discomfort caused by fore-and-aft and lateral vibration.

During horizontal vibration, greatest discomfort is experienced at the interfaces between the body and the seat, consistent with shearing of tissues around the ischial tuberosities. During vertical vibration, greater discomfort is experienced towards the central and upper parts of the body as the magnitude of vibration increases. Widening the distribution of pressure over the surface of a rigid flat seat with a beanbag had no effect on the rate of growth of vibration discomfort, or the frequency-dependence of vibration discomfort, or the locations of greatest discomfort.

Differences in the magnitude-dependence of the frequency-dependence of vibration discomfort and the relative discomfort caused by vertical and horizontal vibration are not reflected in the currently standardised frequency weightings. To better coincide with the frequency-dependence and the direction-dependence of the discomfort caused by whole-body vibration it may be appropriate to develop different weightings for low magnitude and high magnitude vibration.

Chapter 7 Predicting discomfort caused by multi frequency multi-axis random motion of seated passengers.

7.1 Introduction

In the majority of transport situations, humans are exposed to vibration consisting of multiple frequency multi-axis vibration. It is necessary when trying to reduce discomfort in all types of vehicles to be able to evaluate accurately the measured or predicted vibration for human discomfort. This will be dependent on the magnitude, frequency, direction, and duration of the motion.

Studies of seated human discomfort from whole-body vibration tend to focus on single direction, single frequency sinusoidal motion (Griffin *et al.* (1982), Parsons and Griffin (1982), Morioka and Griffin (2006)). It is necessary when trying to see individual effects of motions of each frequency and direction to use simple motions and eliminate as many variables as possible. However, it is also necessary to determine an appropriate strategy for evaluating vibration so as to predict the discomfort of more complex motions that are experienced in real life.

Very few studies have investigated the discomfort produced by combinations of two or more sinusoidal motions. Fothergill and Griffin (1977) described three experiments with vertical vibration investigating the discomfort produced by two non-harmonically matched sinusoidal motions, the discomfort produced by two motions with noticeable beating, and the discomfort produced by a combination of up to four sinusoidal motions. Two methods (the root-mean-square and a masking method) were found to be reasonable predictors of vibration discomfort, with the root-mean-square (r.m.s.) method being favoured because it was easy to apply electronically. It was found that the discomfort caused by one-third octave bandwidth, octave bandwidth, and three-octave bandwidth random whole-body vertical vibration could be predicted from the discomfort caused by sinusoidal vibration (Griffin, 1976).

Fothergill and Griffin (1977) investigated power summation methods for predicting the total acceleration, φ_{total}, required to produce discomfort equivalent to that caused by dual frequency vibration from the acceleration equivalent to φ_a and φ_b caused by each of the two frequency components, *a* and *b*, when they are experienced separately. They investigated the power summation method with different values of the exponent, β:

$$\varphi_{total} = \left(\sum \varphi_i^{\beta}\right)^{1/\beta} \tag{7.1}$$

Two extreme conditions exist with β = 1.0 (acceleration equivalent to the discomfort caused by dual-frequency motion is predicted from the linear summation of the acceleration equivalent to the discomfort caused by the two sources of vibration) and $\beta = \infty$ (acceleration equivalent to the discomfort caused by dual-frequency motion is predicted from the discomfort of the 'worst' component). For the root-sums-of-squares (r.s.s.) method the value of β is 2.0 and for the root-sum-quad (r.s.q.) method the value of β is 4.0. The optimal value of β is that giving the least difference between judgements of vibration discomfort and the predicted vibration φ_{total}.

Griffin and Whitham (1977); Fairley and Griffin (1988) and Mistrot *et al.* (1990) have investigated the discomfort caused by dual-axis motion of seated humans and Thuong and Griffin (2015) have investigated the discomfort caused by dual-axis and tri-axial vibration of standing humans, but there are no known systematic studies of the discomfort caused to seated humans by tri-axial vibration.

Griffin and Whitham (1977) used 3.15 Hz sinusoidal motion in the vertical and lateral directions to determine that phase did not have a large influence over the discomfort caused by dual-axis vibration in orthogonal directions. Mistrot *et al.* (1990) performed a similar experiment using the same frequency in each direction at 3.15 Hz and 6.3 Hz for combinations of vertical and fore-and-aft and vertical and lateral dual-axis motions. Using integer values for power summation (Equation 7.1) it was found that an exponent of 2 or a root-sums-of-squares (r.s.s) method provided the least difference in the results, with lower values overestimating and higher values underestimating discomfort.

Fairley and Griffin (1988) used many sinusoidal motions in different combinations from 2.5 Hz to 10 Hz in the vertical and fore-and-aft directions to determine discomfort caused by dual-axis motion. It was found that an exponent of 2.07 used in a power summation was optimum, suggesting that an r.s.s approach was reasonable. There were some significant differences between the experimental results and those obtained using r.s.s. summation, however this may be explained by noticeable 'beating' in the stimuli caused by the phase of two sinusoids used resulting in various Lissajous' type patterns.

The above studies used intensity matching techniques where each multi-axis or multi-frequency motion was matched by the participants to a single axis sinusoidal motion. Therefore the exponent, β, used in the power summation method was determined by objective acceleration values. Subjective magnitude estimation methods developed after these studies and used in Chapters 4 and 6 of this Thesis allow for a direct mapping of subjective experience. Because of this, it is possible to use subjective magnitudes in a similar way to the objective magnitudes in a power summation, where the subjective magnitudes of single-axis single-frequency motion give values for Ψ_i and subjective magnitudes of multi-axis or multi-frequency motion give values of Ψ_{total} and the value of α represents the summation of subjective magnitudes rather than equivalent objective magnitudes:

$$\psi_{total} = \left(\sum \psi_i^{\alpha}\right)^{1/\alpha} \tag{7.2}$$

Thuong and Griffin (2015) investigated the discomfort of standing persons caused by multi-axis octave-band filtered random vibration centred on 1 Hz and 4 Hz using subjective magnitude estimation. Optimal values of α in a power summation of subjective values were determined at 2.7 for motion centred on 1 Hz and 3.0 for motion centred on 4 Hz. The average of these two values, 2.85, was within the suitable range for both frequencies and so an overall value for the power of 2.85 might be suggested for a power summation method. However, they also considered the rate-of-growth of discomfort, *n*, in Stevens' Power Law, which suggested that the value of α for a power summation of subjective values would be affected by the rate-of-growth of discomfort and this may be related to the power used in the power summation of objective values, β, by Equation 7.3:

$$\psi_{total} = \left(\sum \psi_a^{\beta/n}\right)^{n/\beta} \tag{7.3}$$

$$\alpha = \frac{\beta}{n} \tag{7.4}$$

When using Equation 7.3, it was noted that, using the average rate-of-growth for standing humans, $n = 0.72$ (Thuong and Griffin (2011), and the optimal value of 2.85 for α, that the value of β is 2.05 which is similar to the value of 2 found useful in previous studies with seated people using objective magnitude intensity matching methods. It was pointed out that because the value of *n* depends on the frequency and direction of the motion, the value of β will also depend on the frequency and direction of the motion, although there were no comparisons made using different values of *n* in the paper.

This study was designed to investigate the vibration discomfort caused by single bands of one-octave bandwidth random motions in all three translational directions (fore-and-aft, lateral, and vertical) centred on 2.0, 4.0 or 8.0 Hz, the discomfort caused by single-axis multi-frequency vibration comprised of two or three of the one-octave bandwidth random motions in the same axis, and the discomfort caused by dual-axis or tri-axial motions consisting of one-octave bandwidth motions in two or three of the translational axes.

It was hypothesised that the optimum value of the exponent in a power summation, α, would vary according to the frequencies used and the directions of vibration for single-axis multi-frequency vibration, dual-axis vibration, and tri-axial vibration.

7.2 Method

7.2.1 Participants

Eighteen subjects, nine males and nine females, who were students or office workers at the University of Southampton participated in the study. The male participants had a median age of 29 years (range 22 to 33 y), stature 1.83 m (range 1.69 to 1.88 m), and weight 71 kg (65 to 130 kg). The female participants had a median age of 27 years (range 20 to 31 y), stature 1.61 m (range 1.53 to 1.69 m), and weight 55 kg (50 to 67 kg). The physical characteristics of each subject are reported in Table 7.1.

The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (application number 25213).

7.2.2 Motions

Motion stimuli were generated using MATLAB (version 2012a) and *HVLab* toolbox (version 2). The stimuli consisted of octave-bandwidth random vibrations centred at 2.0, 4.0, and 8.0 Hz (i.e., 1.4 – 2.8 Hz, 2.8 – 5.7 Hz, and 5.7 – 11.3 Hz) with a cut-off rate of 24dB per octave. The stimuli had durations of 7 seconds to ensure the lowest frequency would achieve at least five cycles.

When experimenting with random vibration, some measure, or control, of the amplitude distribution or the peaks in the motion is required. One method is to quantify the crest factor (ratio of the peak to the r.m.s. value of the motion), but this is highly dependent on the magnitude at one instant of time. Another method is to quantify the r.m.s. to r.m.q. ratio, as employed by Thuong and Griffin (2011). In this study, the stimuli were selected from a large number of alternatives so that the ratio between the r.m.s. and r.m.q. was always 1.28. An example stimulus is shown in Figure 7.1.

Table 7.1 Participant characteristics.

Subject	Gender	Age (y)	Height (m)	Weight (kg)
1	F	27	1.57	50
2	M	22	1.83	80
3	M	24	1.83	76
4	M	29	1.88	130
5	F	23	1.59	53
6	M	29	1.86	71
7	M	31	1.69	67
8	M	33	1.72	68
9	M	25	1.88	70
10	F	30	1.53	54
11	F	25	1.61	60
12	F	24	1.69	55
13	F	28	1.60	54
14	F	27	1.69	67
15	M	31	1.81	65
16	M	26	1.87	87
17	F	20	1.67	60
18	F	31	1.67	55

7.2.3 Apparatus

Fore-and-aft, lateral, and vertical random vibration was produced by the six-axis vibration simulator in the Human Factors Research Unit of the Institute of Sound and Vibration Research at the University of Southampton (Figure 7.2).

A rigid flat seat with no backrest (seat-pan height 0.570 m, seat-pan depth 0.493 m) was mounted on the vibration simulator. Subjects sat on a beanbag with a rigid frequency response over the frequency range investigated. Subjects wore a loose lap belt and held an emergency stop button for safety. A rigid footrest was adjusted so that the lower surfaces of the thighs were in contact with the beanbag surface when the heels of the subjects rested on the footrest.

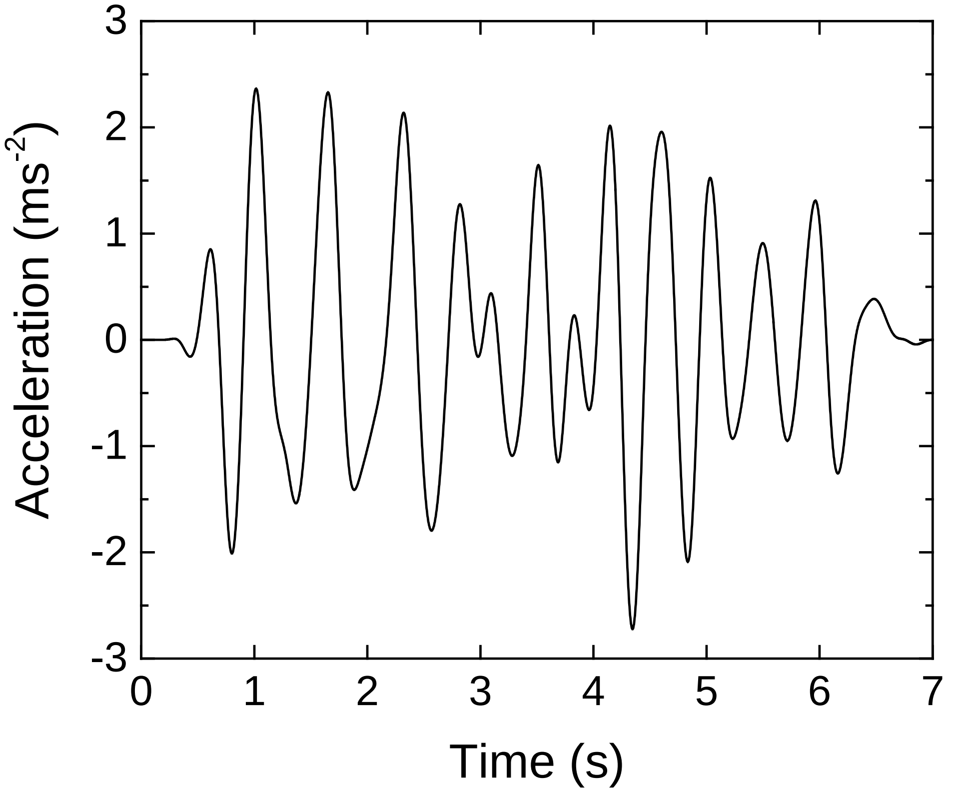

Figure 7.1 Example stimulus, one-octave bandwidth of vertical vibration centred on 2.0 Hz.

Simulator noise was masked by white noise at 65 dB (A) produced through headphones worn by the subjects. The experimenter could see the subjects at all times and communicate with them through the headphones via a microphone.

Each vibration stimulus was adjusted to a frequency-weighted magnitude of 1.0 $m.s^{-1.75}$ VDV (using weighting W_b for vertical vibration and weighting W_d for fore-and-aft and lateral vibration, with unity multiplying factors in accord with British Standard 6841:1987).

The vibration stimuli presented to each subject consisted of the three one-octave bandwidth motions (centred on 2.0, 4.0, and 8.0 Hz) in each of the three directions (fore-and-aft, lateral, vertical). There were nine single-axis single-frequency bandwidth motions, at each of the three frequency bands (2.0, 4.0 and 8.0 Hz) and in all three directions (fore-and-aft, lateral and vertical). All 54 possible combinations of multi-axis vibration (dual-axis or tri-axial) with a single frequency band per axis were reproduced, where vibration in each axis would consist of a motion centred on either 2.0, 4.0, or 8.0 Hz, or no vibration (the condition of no vibration in all three axes was not included). In addition there were a further 12 stimuli of single-axis multiple-frequency octave-band motions in all combinations of 2.0, 4.0, and 8.0 Hz within each axis, giving a total of 75 stimuli.

Figure 7.2 Experimental setup on the 6-axis vibration simulator.

The single-axis motions in which two or three bands were combined were simple summations of the two or three component waveforms. Depending on the phase, there was addition or cancellation of the acceleration magnitude at each instant in time and so the VDVs of the combined motions differed from the fourth root of the sum of the fourth powers of the component motions. An example of a combined stimulus formed from two one-octave bandwidths of random vibration is given in Figure 7.3.

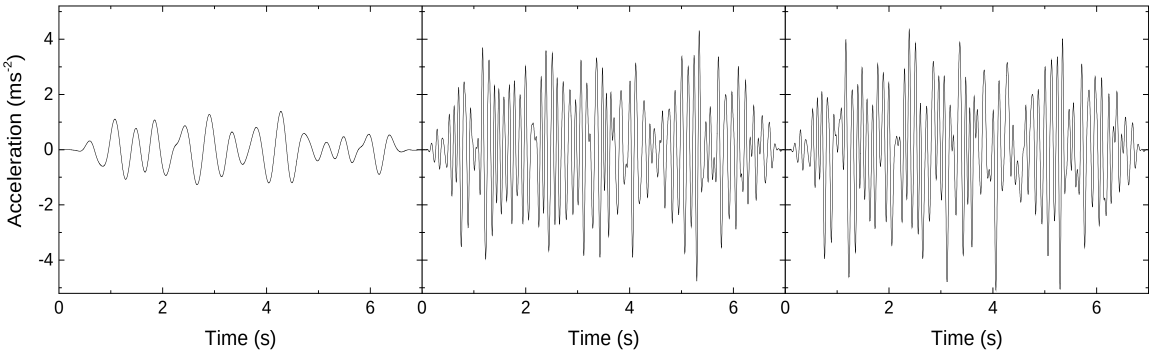

Figure 7.3 Example time histories of two one-octave bandwidth random fore-and-aft vibrations (centred on 2.0 Hz and 8.0 Hz) summed together to form a combined stimulus.

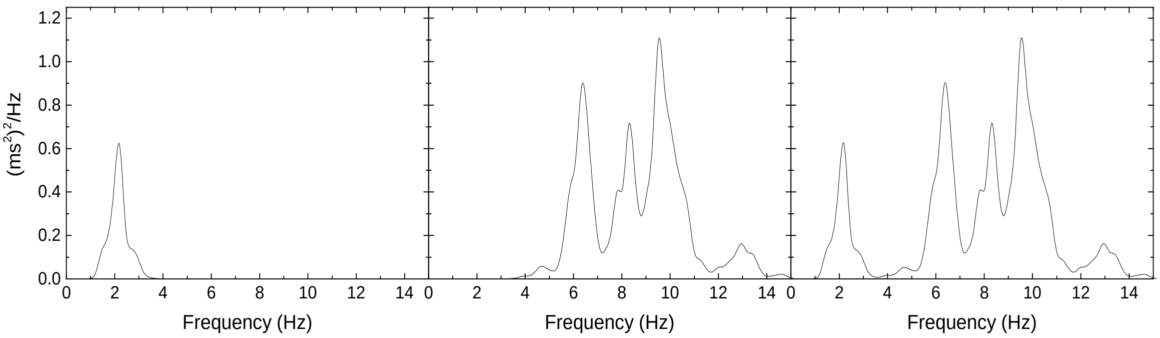

Figure 7.4 Example spectra of two one-octave bandwidth random fore-and-aft vibrations (centred on 2.0 Hz and 8.0 Hz) summed together to form a combined stimulus.

7.2.4 Procedure

Subjects attended one session lasting approximately 90 minutes, which included reading instructions, signing a consent form, practice, and participating in the experiment. Practice consisted of using magnitude estimation to judge the length of lines on paper and then judging vibration discomfort when exposed to six vibrations (over the range of frequencies and all three directions of vibration they would experience during the experiment).

During the experiment, the subjects closed their eyes to eliminate any influence of the visual perception of motion on their judgements. They were instructed to sit comfortably and maintain the same upright posture at all times.

Subjects rated the vibration discomfort caused by each of the motions using the method of absolute magnitude estimation. They were encouraged to give a rating of 100 for the first motion they experienced (one-octave bandwidth tri-axial random vibration centred on 4.0 Hz with a frequency-weighted vibration dose value of 0.87 $ms^{-1.75}$ in each direction). They were asked to rate the discomfort caused by all subsequent motions relative to the discomfort caused by the first motion. It was explained that a rating of 50 would mean the discomfort was half that caused by the first motion, and that a discomfort of 200 would mean the vibration discomfort was double that caused by the first motion. The order of presenting the frequency, direction, and number of frequency bands was randomised independently for each subject. The subjects were provided written instructions that are shown in Appendix A.

Every stimulus was presented to a subject three times in three separate blocks within the experiment. To adjust for any systematic change in ratings of discomfort given by each subject over the experiment, the magnitude estimates of discomfort given by subjects within a block were adjusted using the same method as in Chapter 4 to give a median magnitude estimate of 100. The median magnitude estimate for each of the 75 motions over the three blocks was used as the magnitude estimate of that motion by the subject.

7.2.5 Data analysis

The median magnitude estimate given by each subject was compared with the predicted magnitude estimate calculated for each value of α between 1.0 and 10.0 in steps of 0.01. The difference between the measured and predicted discomfort was then calculated for each individual with each combination of stimuli and each value of α. The median difference over all 18 subjects was determined for each value of α, and the optimum value of α for each combination of stimuli identified where the median difference was a minimum.

7.2.6 Statistical tests

The hypotheses were tested using non-parametric statistics in SPSS (version 22). The Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks were used to test for differences between related samples. The Spearman's rho was used to test for correlations between results.

7.3 Results

The percentage errors referred to in this section correspond to the median difference between the predicted and measured discomfort, using different values for α, as a percentage of the measured discomfort. The median errors were calculated separately for each of the 66 multiple-frequency or multiple-axis stimuli.

7.3.1 Within individual axes (all single-axis motions)

Table 7.2 shows the median percentage error between the predicted and measured discomfort using values of 1, 2, 4, and ∞ for α in Equation 7.2 for the 12 single-axis multi-frequency combinations. A positive number represents an overestimation of discomfort and a negative number represents an underestimation of discomfort.

Table 7.2 Summary of median percentage errors for different value of α in Equation 7.2 and the optimum value for α for the 12 single-axis multi-frequency stimuli.

Stimulus	% error α = 1	% error α = 2	% error α = 4	% error α = ∞	Optimum α value
x 2.0 *x* 4.0	41.67**	3.02	-10.50*	-17.73**	2.21
x 2.0 *x* 8.0	57.92**	15.19	2.05	-4.55	5.50
x 4.0 *x* 8.0	45.87**	4.91	-10.26*	-17.36**	2.40
x 2.0 *x* 4.0 *x* 8.0	81.82**	8.73**	-13.50**	-26.14**	2.38
y 2.0 *y* 4.0	46.94**	5.64	-10.22*	-17.00**	2.36
y 2.0 *y* 8.0	42.54**	1.46	-8.54**	-18.18**	2.10
y 4.0 *y* 8.0	61.36**	19.72*	3.73	-9.05	5.28
y 2.0 *y* 4.0 *y* 8.0	85.85**	7.48	-15.44**	-25.21**	2.31
z 2.0 *z* 4.0	45.00**	7.24	-8.03	-17.42*	2.51
z 2.0 *z* 8.0	38.03**	-0.02	-13.04	-18.29*	2.00
z 4.0 *z* 8.0	61.98**	17.25*	-3.45	-14.40*	3.16
z 2.0 *z* 4.0 *z* 8.0	100.61**	18.13*	-8.56*	-23.00**	2.89

* Significant difference (p<0.05, Wilcoxon)

** Significant difference (p<0.01, Wilcoxon)

There were no statistically significant differences in the optimum values of α across the 12 combinations of four frequencies and three axes shown in Table 7.2 (p>0.05, Friedman). With no statistically significant effects of frequency or direction of vibration on the optimum power for summation, it seems reasonable to determine an optimum single value of α across all combinations of frequency over all three directions. Percentage errors were calculated for each participant for all combinations of two and three frequency bands. The median error over all combinations of frequency and all three directions over the group of subjects was a minimum when α = 2.54.

Comparisons between magnitude estimates of vibration discomfort and predictions of vibration discomfort are shown in Figure 7.5, using the above values of α that give the least error within each axis. The dependence of the median error on the power *α* are shown for each direction of vibration in Figure 7.6.

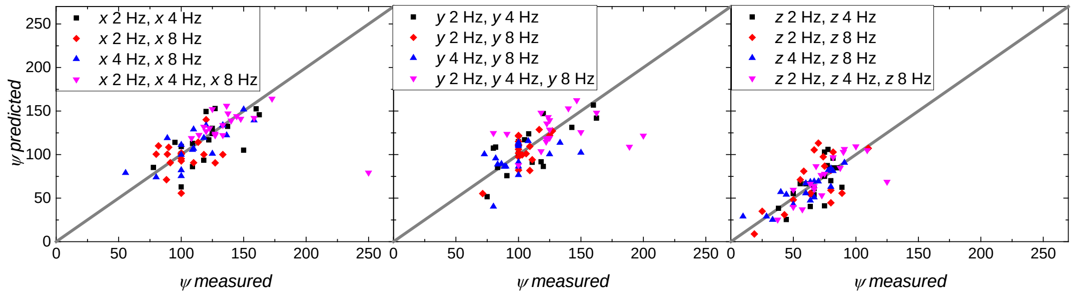

Figure 7.5 Scattergrams between median ratings of vibration discomfort and median predictions of vibration discomfort caused by combined frequency vibrations using optimum values of *α* for each condition (see Section 7.3.2). Ratings are from 18 subjects and four combinations of frequency for each direction. Conditions where $\psi_{\text{predicted}} = \psi_{\text{measured}}$ shown by diagonal lines.

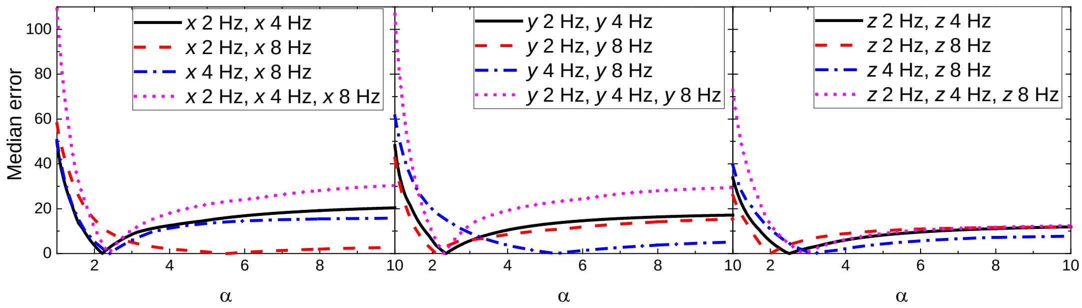

Figure 7.6 Dependence of median error between judgements of vibration discomfort and predictions of single-axis multiple-frequency vibration discomfort for values of *α* between 1.0 and 10.0 in steps of 0.01.

7.3.2 Dual-axis stimuli

Table 7.3 shows the median percentage error between the predicted and measured discomfort using values of 1, 2, 4, and ∞ for *α* in Equation 7.2 for the 27 dual-axis combinations. A positive number represents an overestimation of discomfort and a negative number represents an underestimation of discomfort.

Table 7.3 Summary of median percentage errors for different value of α in Equation 7.2 and the optimum value for α for the 27 dual-axis stimuli.

Stimulus	% error α = 1	% error α = 2	% error α = 4	% error $\alpha = \infty$	Optimum α value
x 2.0 *y* 2.0	47.62**	2.79	-13.48*	-18.65**	2.17
x 2.0 *y* 4.0	44.94**	5.80	-7.89	-17.50**	2.58
x 2.0 *y* 8.0	28.64**	-3.89	-11.18**	-18.80**	1.71
x 4.0 *y* 2.0	34.47**	-0.39	-14.00**	-19.95**	1.97
x 4.0 *y* 4.0	47.08**	5.49	-9.96*	-17.69**	2.47
x 4.0 *y* 8.0	38.37**	1.14	-11.64**	-17.36**	2.08
x 8.0 *y* 2.0	51.67**	10.46	-4.79	-10.33	3.07
x 8.0 *y* 4.0	79.41**	25.86**	7.87	0.00	45.00
x 8.0 *y* 8.0	52.78**	9.22	-7.98*	-18.18**	2.57
x 2.0 *z* 2.0	33.75**	2.18	-7.65	-10.56**	2.17
x 2.0 *z* 4.0	40.75**	6.66	-5.93	-13.50*	2.66
x 2.0 *z* 8.0	42.23*	3.74	-3.96	-13.57	2.56
x 4.0 *z* 2.0	42.79**	8.43	-0.18	-7.11*	3.88
x 4.0 *z* 4.0	35.68**	2.34	-8.67	-17.84*	2.22
x 4.0 *z* 8.0	36.74*	-2.65	-15.02	-19.25*	1.86
x 8.0 *z* 2.0	61.88**	16.94	-0.44	-9.11	3.89
x 8.0 *z* 4.0	54.47**	10.20	-3.42	-8.82	3.18
x 8.0 *z* 8.0	46.31**	14.48	0.19	-6.46	4.07
y 2.0 *z* 2.0	43.25**	4.11	-10.51	-16.08*	2.31
y 2.0 *z* 4.0	50.48**	7.14	-3.63	-11.20	3.12
y 2.0 *z* 8.0	43.47*	2.26	-13.05	-20.58*	2.17
y 4.0 *z* 2.0	45.69**	8.99	-4.64	-17.79*	3.09
y 4.0 *z* 4.0	53.17**	13.59*	-0.06	-1.73	3.97
y 4.0 *z* 8.0	43.33**	15.87*	2.63	-0.81	7.10
y 8.0 *z* 2.0	47.52**	10.47	-2.03	-6.39	3.32
y 8.0 *z* 4.0	45.48**	9.58	-3.81	-7.37*	3.12
y 8.0 *z* 8.0	43.55**	6.81	-6.71	-10.95**	2.43

* Significant difference ($p<0.05$, Wilcoxon)

** Significant difference ($p<0.01$, Wilcoxon)

For dual-axis motions there were statistically significant differences in the value of the exponent between stimuli (p=0.018, Friedman). This suggests that it would be inappropriate to use a single value for the exponent in this case. Using the Wilcoxon matched-pairs test, it was possible to detect which groups of stimuli are causing the differences, this comparison can be seen in Appendix C. This shows that the statistically significant Friedman test was largely determined by the combination of 8-Hz fore-and-aft vibration and 4-Hz lateral vibration, where subjects rated this combined motion less uncomfortable than predicted from the discomfort of the two components separately. This was because both 8-Hz fore-and-aft vibration and 4-Hz lateral vibration had high measured discomfort as individual motions.

Comparisons between subjective judgements of vibration discomfort and predictions of vibration discomfort are shown in Figure 7.7, using the values of α giving the least error for each condition. The dependence of the median error on the power α are shown for each direction of vibration in Figure 7.8.

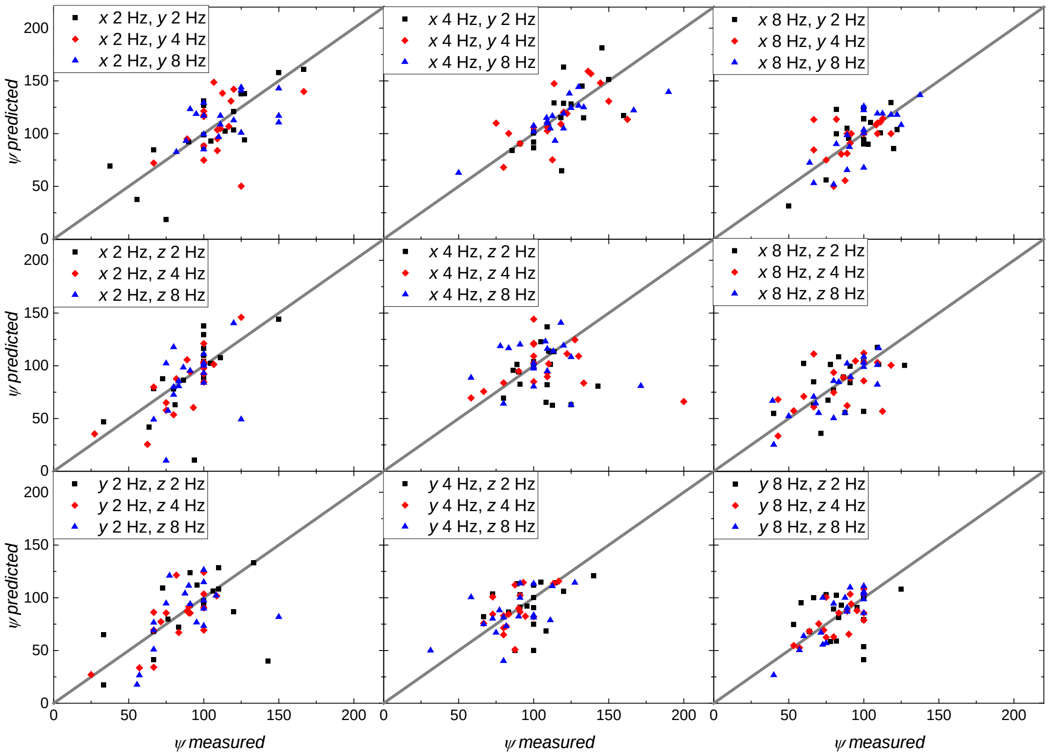

Figure 7.7 Scattergrams between ratings of vibration discomfort and predictions of vibration discomfort caused by combined frequency vibrations using optimum values of α for each condition (see Section 7.3.3). Ratings are from 18 subjects and 3 combinations of frequency and direction. Conditions where $\psi_{\text{predicted}} = \psi_{\text{measured}}$ shown by diagonal lines.

A few very extreme underestimations can be seen in Figure 7.7 (e.g. the centre graph representing fore-and-aft vibration at 4.0 Hz combined with vertical vibration at 2.0, 4.0, and 8.0 Hz). These underestimations are from a single participant caused by extremely low magnitude estimations of the single-axis component motions compared with the multi-axis estimations. As the optimal value for α was calculated from median values, this outlier had no effect on the conclusions.

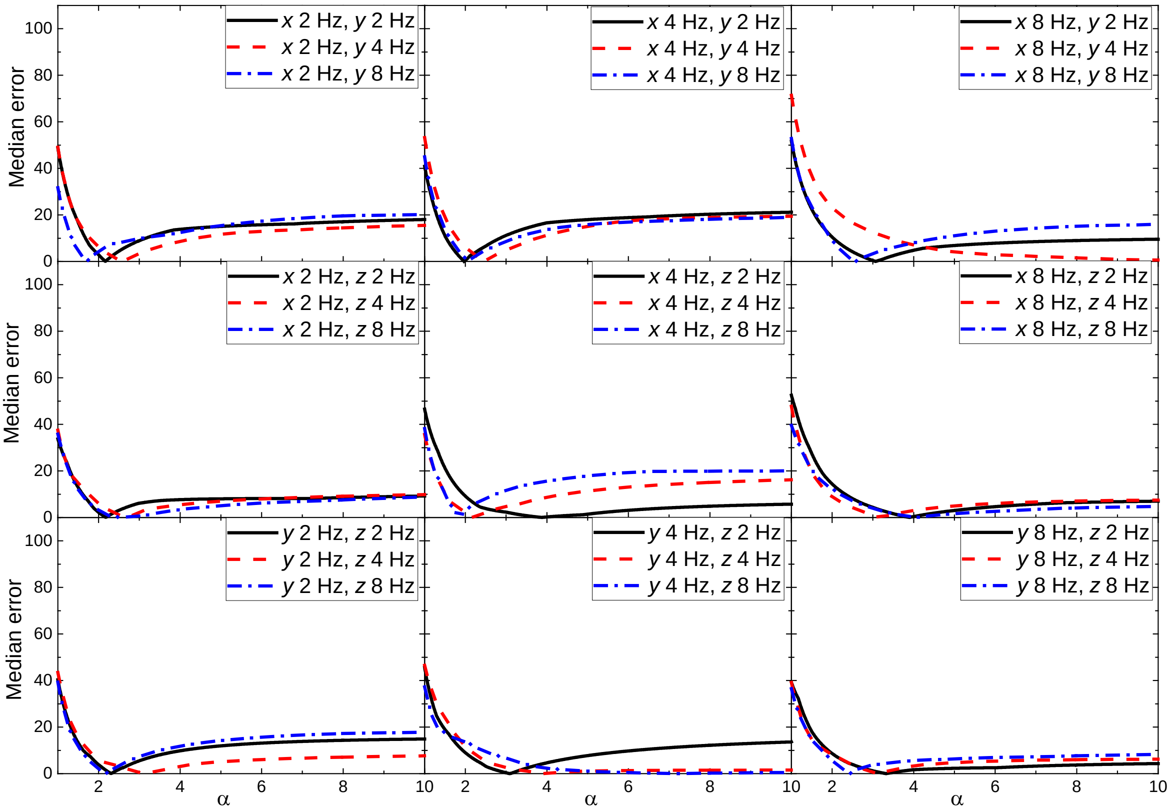

Figure 7.8 Dependence of median error between judgements of vibration discomfort and predictions of dual-axis vibration discomfort for values of α between 1.0 and 10.0 in steps of 0.01.

7.3.3 Tri-axial stimuli

Table 7.4 shows the median percentage error between the predicted and measured discomfort using values of 1, 2, 4, and ∞ for α in Equation 7.2 for the 27 tri-axial combinations. A positive number represents an overestimation of discomfort and a negative number represents an underestimation of discomfort.

Table 7.4 Summary of median percentage errors for different value of α in Equation 7.1 and the optimum value for α for the 27 tri-axial stimuli.

Stimulus	% error α = 1	% error α = 2	% error α = 4	% error $\alpha = \infty$	Optimum α value
x 2.0 *y* 2.0 *z* 2.0	55.57**	-4.33	-29.03**	-35.63**	1.86
x 2.0 *y* 2.0 *z* 4.0	66.00**	0.23	-19.75**	-27.88**	2.01
x 2.0 *y* 2.0 *z* 8.0	69.89*	2.07	-19.74**	-31.59**	2.09
x 2.0 *y* 4.0 *z* 2.0	82.21**	11.39	-12.63*	-25.52**	2.67
x 2.0 *y* 4.0 *z* 4.0	74.91**	6.15	-12.55*	-22.36**	2.27
x 2.0 *y* 4.0 *z* 8.0	80.15**	7.93	-15.43**	-30.15**	2.34
x 2.0 *y* 8.0 *z* 2.0	74.35**	11.70	-9.95**	-19.83**	2.72
x 2.0 *y* 8.0 *z* 4.0	88.19**	11.97	-14.87*	-21.11**	2.45
x 2.0 *y* 8.0 *z* 8.0	78.38**	9.50	-9.58*	-18.33**	2.58
x 4.0 *y* 2.0 *z* 2.0	70.25*	2.27	-14.73**	-25.84**	2.10
x 4.0 *y* 2.0 *z* 4.0	64.44**	-1.34	-21.40**	-31.37**	1.95
x 4.0 *y* 2.0 *z* 8.0	61.66**	-2.48	-21.16**	-28.21**	1.91
x 4.0 *y* 4.0 *z* 2.0	88.14**	12.93	-11.10*	-26.85**	2.67
x 4.0 *y* 4.0 *z* 4.0	81.09**	8.55	-14.99*	-22.97**	2.37
x 4.0 *y* 4.0 *z* 8.0	89.89**	9.40*	-13.06*	-25.74**	2.43
x 4.0 *y* 8.0 *z* 2.0	82.22**	9.47	-11.38*	-22.52**	2.51
x 4.0 *y* 8.0 *z* 4.0	66.06**	3.97	-15.45**	-22.00**	2.21
x 4.0 *y* 8.0 *z* 8.0	79.13**	10.93	-8.37	-18.03**	2.78
x 8.0 *y* 2.0 *z* 2.0	87.95**	11.90	-10.15	-15.75**	2.63
x 8.0 *y* 2.0 *z* 4.0	89.49**	14.11*	-7.71	-11.79**	2.73
x 8.0 *y* 2.0 *z* 8.0	87.88**	11.62*	-7.23	-20.00*	2.86
x 8.0 *y* 4.0 *z* 2.0	113.93**	27.35**	6.47	-1.29	9.69
x 8.0 *y* 4.0 *z* 4.0	102.85**	25.96**	-2.19	-15.55*	3.65
x 8.0 *y* 4.0 *z* 8.0	100.00**	23.94**	-0.51	-17.42*	3.88
x 8.0 *y* 8.0 *z* 2.0	104.39**	29.02**	5.21	-10.56*	5.54
x 8.0 *y* 8.0 *z* 4.0	93.18**	13.22*	-10.81*	-20.00**	2.66
x 8.0 *y* 8.0 *z* 8.0	112.01**	15.58*	-10.33	-21.30**	2.83

* Significant difference (p<0.05, Wilcoxon)

** Significant difference (p<0.01, Wilcoxon)

With tri-axial motions there were also statistically significant differences in the value of the exponent between stimuli (p=0.000, Friedman). This suggests that it would be inappropriate to use a single value for the exponent. Using Wilcoxon matched-pairs tests it was possible to see which groups of stimuli were causing the differences, this comparison can be seen in Appendix C. The Table in Appendix C shows that statistically significant differences occurred systematically between pairs of stimuli when the frequency of the fore-and-aft and/or lateral component of the tri-axial motion was different, the vertical component does not seem to have had the same systematic effect.

Comparisons between subjective judgements of vibration discomfort and predictions of vibration discomfort are shown in Figure 7.9, using the above values of α to give the least error for each condition. The dependence of the median error on the power α are shown for each direction of vibration in Figure 7.10.

A few extreme underestimations can be seen in Figure 7.9 (e.g. the top centre graph representing fore-and-aft vibration at 4.0 Hz combined with lateral vibration at 2.0, 4.0, and 8.0 Hz combined with vertical vibration at 2.0 Hz). These underestimations are from the same participant who gave deviant judgements with the dual-axis motions and were again caused by extremely low magnitude estimations of the single-axis component motions compared with the multi-axis estimations. As the optimal value for α was calculated from median values, this outlier had no effect on the conclusions.

7.3.4 The effect of rate of growth on the value of the exponent

From a previous experiment (Chapter 6), the rate-of-growth in the fore-and-aft and lateral directions reduces with increasing frequency, with peaks around 2.5 and 1.6 for fore-and-aft and lateral vibration, respectively. This variation in the rate-of-growth of discomfort may explain differences between motions with low-frequency fore-and-aft and lateral components and motions without low frequency fore-and-aft and lateral components.

Average values for the rates-of-growth taken from the one-third octave components from the previous experiment (Chapter 6) over the frequency range covered by each octave band used in this experiment were calculated and are presented in Table 7.5.

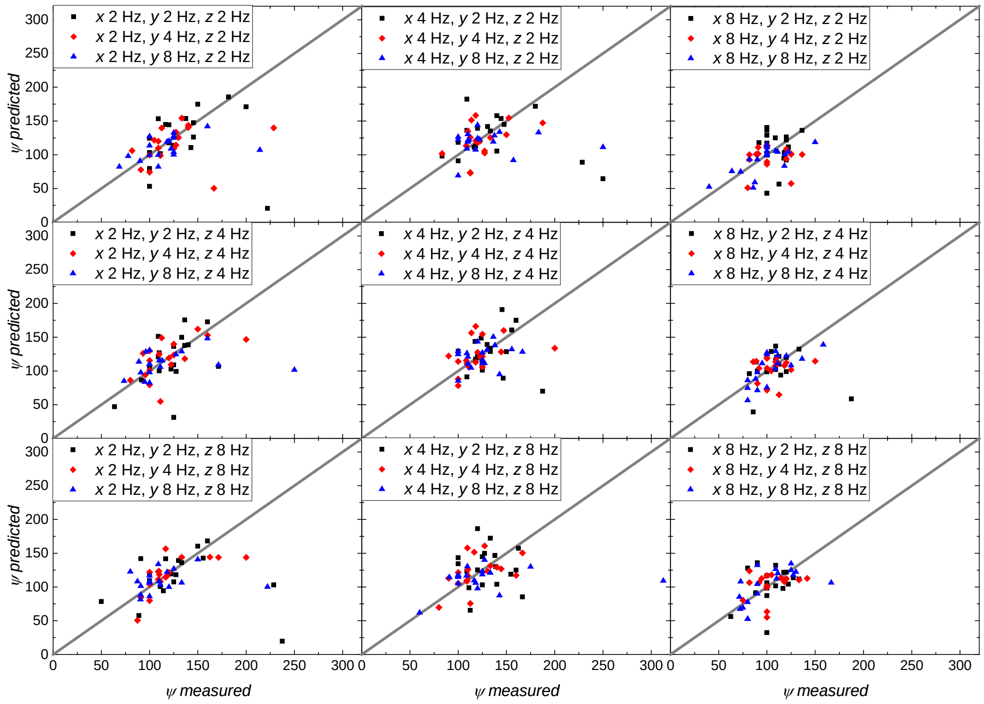

Figure 7.9 Scattergrams between ratings of vibration discomfort and predictions of vibration discomfort caused by combined frequency vibrations using optimum values of α for each condition (see Section 7.3.4). Ratings are from 18 subjects and 3 combinations of frequency and direction. Conditions where $\psi_{\text{predicted}} = \psi_{\text{measured}}$ shown by diagonal lines.

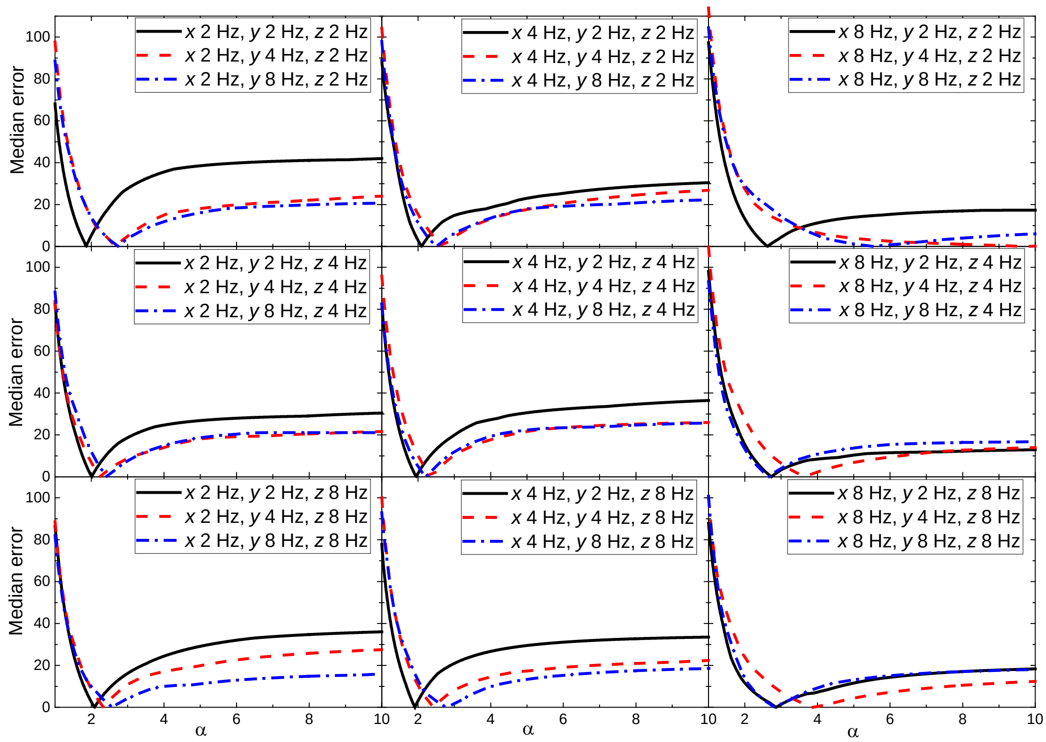

Figure 7.10 Dependence of median error between judgements of vibration discomfort and predictions of tri-axis vibration discomfort for values of α between 1.0 and 10.0 in steps of 0.01.

Table 7.5 Summary of average rates-of-growth of discomfort, *n*, from Chapter 6 produced by single-frequency sinusoidal motion.

	Fore-and-aft	Lateral	Vertical
2 Hz	0.63	0.61	0.68
4 Hz	0.40	0.38	0.70
8 Hz	0.36	0.30	0.57

Spearman's rho correlation was calculated between optimal values of α for tri-axial motions (Table 7.3, right hand column) and the average of the component rates-of-growth (for each stimulus combination; e.g. for the 2.0 Hz fore-and-aft, 2.0 Hz lateral, 2.0 Hz vertical combined vibration the median rates of growth are 0.63, 0.61, and 0.68 respectively, the average is 0.64) shown in Table 7.5. The correlation was highly significant (p=0.000, Spearman's rho) suggesting that the rate-of-growth of discomfort had an influence on the exponent used in the power summation method. Figure 7.11 shows the correlation.

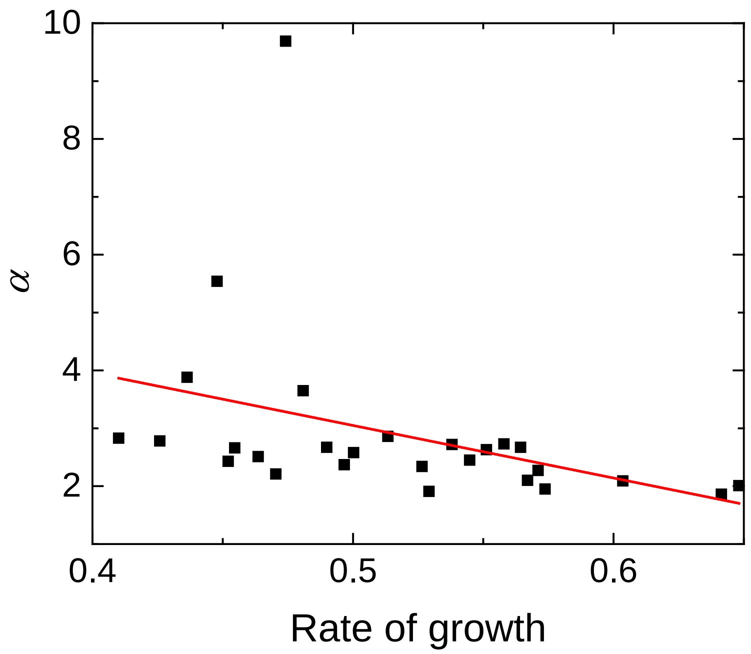

Figure 7.11 Relationship between the average rate of growth of discomfort from Chapter 6 and the optimal exponent α in the current experiment for tri-axial combinations.

The Spearman's rho correlation was also calculated between optimal values of α and the average rate-of-growth of discomfort for single-axis multiple-frequency vibration and dual-axis vibration. These were found not to be correlated (p>0.05, Spearman's rho).

7.4 Discussion

7.4.1 Power summation methods

7.4.1.1 Single-axis multi-frequency vibration

For all single-axis multi-frequency vibrations, Table 7.2, the linear sum method corresponding to α = 1 in Equation 7.2 significantly overestimated vibration discomfort for all combinations of frequency in all axes. The worst component method, corresponding to $\alpha = \infty$ in Equation 7.2 significantly underestimated discomfort in all but two combinations. A root-sums-of-squares (r.s.s.) method, corresponding to α = 2, significantly overestimated discomfort in four stimuli with up to 19.72% error and a root-sum-quad (r.s.q.) method, corresponding to α = 4, significantly underestimated discomfort in seven stimuli with up to 15.44% error. This suggests that none of the above methods accurately predict discomfort using subjective measurements.

A single exponent α of 2.54 was found to predict discomfort without statistically significant differences across all frequency combinations in all three axes.

7.4.1.2 Dual-axis vibration

For all dual-axis vibrations, Table 7.3, the linear sum method, corresponding to α = 1 in Equation 7.2 significantly overestimated vibration discomfort for all combinations of frequency in all axes. The worst component method, corresponding to $\alpha = \infty$ in Equation 7.2 significantly underestimated discomfort in all but nine combinations. An r.s.s. method, corresponding to α = 2, significantly overestimated discomfort in three stimuli with up to 25.86% error and an r.s.q. method, corresponding to α = 4, significantly underestimated discomfort in six stimuli with up to 14.00% error. This suggests that none of the above methods accurately predict discomfort using subjective measurements.

The optimal value of α differed significantly across dual-axis stimuli and therefore it is not reasonable to suggest a single value for the exponent. However, looking at the data shown in Appendix C, it can be seen that most of the significant differences were caused by a single stimulus, 8.0 Hz fore-and-aft vibration combined with 4.0 Hz lateral motion. Recordings taken from the simulator platform show that this motion was reproduced as expected so there should not be a problem with the implementation of the experimental design. Magnitude estimations of the discomfort caused by 8.0-Hz fore-and-aft vibration and 4.0-Hz lateral vibration were generally greater than at other frequencies and directions without corresponding increases in the magnitudes estimates of discomfort for the combined motions that contained these components.

7.4.1.3 **Tri-axial vibration**

For all tri-axial vibrations, Table 7.4, the linear sum method, corresponding to α = 1 in Equation 7.2 significantly overestimated vibration discomfort for all combinations of frequency in all axes. The worst component method, corresponding to $\alpha = \infty$ in Equation 7.2 significantly underestimated discomfort in all but one combination. An r.s.s. method, corresponding to α = 2, significantly overestimated discomfort in nine stimuli with up to 29.02% error and an r.s.q. method, corresponding to α = 4, significantly underestimated discomfort in eighteen stimuli with up to 29.03% error. This suggests that none of the above methods accurately predict discomfort using subjective measurements.

The optimal value of α differed significantly across tri-axial stimuli and therefore it is not reasonable to suggest a single value for the exponent. However, looking at the data shown in Appendix C, it can be seen that most of the significant differences occurred when the frequency of the fore-and-aft and/or lateral motion was different between two stimuli, with few significant differences occurring between motions where the vertical component has changed frequency. The vertical component may not have had as large an effect on the value of α, because the rate-of-growth in the vertical direction does not vary as greatly as the rate-of-growth in the fore-and-aft and lateral directions over the frequency range 1 to 10 Hz (see Chapter 6). In addition, in Table 7.4, it can be seen that α = 2 significantly overestimates discomfort only when the frequency of the fore-and-aft component is at 8.0 Hz. Almost the reciprocal is true when α = 4, significant underestimation occurs when the frequency of the fore-and-aft motion is either 2.0 or 4.0 Hz.

Chapter 6 shows that the rate of growth for both fore-and-aft and lateral vibration decreases with increasing frequency. For tri-axial motion in this experiment, the average rate of growth of discomfort from each component was highly correlated with the optimal value of α, suggesting that the value of α may be dependent on the rate of growth of discomfort for the components of the vibration. This was not the case for single-axis or dual-axis motion and may require further investigation. If the value of α in Equation 7.2 depends on the rate of growth of vibration, it is not possible to have a single value of α that is accurate across the whole frequency range in each axis of vibration.

7.4.2 Previous experiments

Previous experiments of seated multi-axis vibration discomfort (Griffin and Whitham, 1977; Fairley and Griffin 1988; Mistrot *et al.*, 1990) have used objective methods (i.e., intensity matching) that assume discomfort is linearly related to vibration magnitude. In each experiment the r.s.s. approach was found to be the most accurate power summation method, although integer values were privileged by Mistrot *et al.* (1990).

Since those experiments, further research has found that discomfort, or subjective magnitude, is not linearly related to vibration magnitude (e.g., Morioka and Griffin, 2006; Wyllie and Griffin 2007; Basri and Griffin, 2013; Zhou and Griffin, 2014). The discomfort of seated persons, ψ, produced by sinusoidal vibration varies as a function of acceleration magnitude, φ, in accordance with Stevens' power law:

$$\psi = k\varphi^{n} \tag{7.5}$$

For seated persons, the rate-of-growth of discomfort, *n*, depends on the direction and frequency of the vibration (Chapters 4 and 6; Morioka and Griffin, 2006; Wyllie and Griffin 2007, Basri and Griffin 2013). It is reasonable to assume that the rate-of-growth will affect the way vibration discomfort increases or decreases when adding or removing axes of vibration.

The general power summation method used above for tri-axial motion is:

$$\psi_{total} = \left[(\psi_x)^{\alpha} + \left(\psi_y\right)^{\alpha} + (\psi_z)^{\alpha}\right]^{1/\alpha} \tag{7.6}$$

Stevens' power law states that the subjective magnitude of fore-and-aft vibration is related to the acceleration magnitude of the fore-and-aft vibration by:

$$\psi_x = k_x {a_x}^{n_x} \tag{7.7}$$

and similarly for lateral vibration, vertical vibration, and total tri-axial vibration (with the subscripts changed to *y*, *z*, and *total*, respectively). Substituting the acceleration magnitude into Equation 7.6:

$$k_i {a_{total}}^{n_i} = \left[(k_x {a_x}^{n_x})^{\alpha} + \left(k_y {a_y}^{n_y}\right)^{\alpha} + (k_z {a_z}^{n_z})^{\alpha}\right]^{1/\alpha} \tag{7.8}$$

and taking the rate-of-growth from each parentheses:

$$k_i {a_{total}}^{n_i} = \left[\left({k_x}^{1/n_x} a_x\right)^{n_x\alpha} + \left({k_y}^{1/n_y} a_y\right)^{n_y\alpha} + \left({k_z}^{1/n_z} a_z\right)^{n_z\alpha}\right]^{1/\alpha} \tag{7.9}$$

If the assumption is made that the sensation of vibration magnitude is summed with equal importance within the body, and thus α is the same for each direction, the exponent for physical summation of acceleration magnitudes is dependent on the rate-of-growth of discomfort, n, for each direction. So it is inappropriate to use the same exponent for each axis for the power summation of objective values.

It is shown in Chapter 6 that the rate-of-growth of discomfort, n, varies with frequency as well as direction. If the variables from Equation 7.9 are altered to represent motions differing in frequency but produced within the same axis, it is possible to also suggest that a single exponent is also inappropriate for summing multiple frequency single axis motion.

To see if there was an improvement in the results, α values for dual-axis and tri-axial combinations were multiplied by the average rate-of-growth for each stimulus from Table 7.4. Friedman tests from these new values revealed highly significant differences in the optimum rate of growth (i.e., α values; $p<0.001$, Friedman), suggesting the average rate-of-growth across the stimuli may not be suitable and the influence of the rate-of-growth of discomfort on the optimum power for summing discomfort over axes of vibration requires further consideration.

Thuong and Griffin (2015) suggested that a different exponent, β, could be used when describing a power summation of acceleration magnitudes to distinguish the difference between the power summation of objective or subjective values. As seen above, the value of β depends on the direction and frequency content of each vibration component, however, without further investigation and to allow for the evaluation of vibration discomfort from measured values, it is practical to consider β as a single integer value.

7.4.3 Current prediction methods

Current British and International standards (BS 6841:1987 and ISO 2631-1:1997) advocate the use of r.m.s. averaging, or r.m.q. averaging for single axis vibration, and r.s.s. summation and r.s.q. summation of multiple axes of vibration. Tables 7.2 to 7.4 show that most often the value of α for subjective summation lies between 2 and 4. If n is equal to 1.0, these values of α could be used directly as values of β in objective summations, however the experiment in Chapter 6 shows that for sinusoidal motion in the range of 1 to 10 Hz in the three translational directions, n can be either greater than 1.0 or less than 1.0. In either case, $\alpha \neq \beta$, and therefore to calculate values of β to be compared with the standards and previous experiments using objective measurements (e.g., Fairley and Griffin (1988), Mistrot *et al.* (1990)) the value of n should influence the value of β used in objective summations. Considering the optimal value of α mostly lies between 2 and 4 in this experiment, it's reasonable to suggest that where $n < 1$, $\beta = 2$ will be a better predictor and where $n > 1$, $\beta = 4$ will be a better predictor.

Median averages across the error produced by $\alpha = 2$ and $\alpha = 4$ are 8.64% and -9.77%, respectively. Considering this, the value of n often being less than 1, and the current method advocated by the British Standard (6841:1987) it is recommended that the use of the r.s.s. method is continued despite potentially overestimating discomfort. However, optimum values of α and β for complex motion of seated subjects merit further consideration.

7.5 Conclusions

The findings of this study show that the linear sum and the worst component methods of predicting vibration discomfort from subjective ratings of vibration discomfort overestimate and underestimate vibration discomfort, respectively.

Ideal values of the power to be used to predict the discomfort caused by single-axis vibration were not significantly different within single-axis multi-frequency vibration (over the frequency range studied: 1.4 to 11.3 Hz) or between directions of vibration (fore-and-aft, lateral, or vertical).

Ideal values of the power to be used to predict the caused by multi-axis vibration (two or three axes) differed significantly from each other, suggesting that no single value is entirely appropriate for use.

When summing objective measures of vibration magnitude, the exponent β is related to the exponent α by the rate-of-growth of discomfort. There are two methods for the summation of objective values advocated in current standards: r.s.s. and r.s.q. Considering the optimum value of α is mostly between 2 and 4, where the rate-of-growth of discomfort is less than 1.0, the r.s.s. summation method may give the best prediction and where the rate-of-growth is greater than 1.0, the r.s.q. may give the best prediction of discomfort.

There is a correlation between the value of the exponent, α, and the average rate-of-growth of discomfort for the frequency bands employed in Chapter 6, suggesting that the optimum power summation depends on the rate-of-growth of discomfort for each component of a vibratory stimulus.

Further investigation is required to determine how the rate-of-growth of vibration discomfort and the optimum exponent in the power summation method using both objective and subjective methods are related.

Chapter 8 General Discussion

8.1 Introduction

The objectives of this thesis were to: i) advance understanding of the effects of a backrest on the rate of growth of discomfort caused by pitch oscillation, ii) advance understanding of how the rate of growth of discomfort affects the frequency-dependence of discomfort caused by translational vibration at different magnitudes, and iii) advance understanding how the rate of growth of discomfort affects the discomfort caused by multi-axis translational vibration.

This chapter discusses the specific questions raised at the end of the literature review that this work sought to answer:

I. How does a backrest affect the rate-of-growth of vibration discomfort and equivalent comfort contours for the pitch oscillation of seated persons over the frequency range of 0.5 to 5.0 Hz?

II. How does the magnitude-dependence of the frequency-dependence of vibration discomfort affect the inter-axis equivalence of discomfort for the vibration of seated persons in the fore-and-aft, lateral, and vertical axes over the frequency range of 1.0 to 10 Hz?

III. When using a power summation method to predict the discomfort caused by octave-bandwidths of random multi-axis vibration, what power is appropriate, and does the rate of growth of discomfort affect the optimum value used in the power summation?

8.2 The subjective response to pitch oscillation with and without a backrest.

8.2.1 Rate of growth of discomfort

The work presented in Chapter 4 of this thesis shows that the rate-of-growth of discomfort caused by pitch oscillation differs depending on whether a backrest is present or not. The exponent, n, in Stevens' power law is similar for both conditions at frequencies less than 1 Hz (Figure 8.1), this is because the main factor causing vibration discomfort at these frequencies is the gravitational component caused by the inclination, θ, of the seat surface (equivalent to an acceleration of $g \sin \theta$). Rotational displacements are greater at lower frequencies and therefore acceleration due to gravity is greater at lower frequencies. As the frequency of oscillation increases, for the same rotational acceleration, the rotational displacement decreases. This causes the mechanism dominating vibration discomfort to change from the acceleration due to gravity to the acceleration at the interface between the seat surfaces and the human occupant and the transmission of this vibration into the body.

In the condition without the backrest, the rate of growth of discomfort caused by pitch oscillation decreased greatly with increasing frequency. The torso does not rotate by the same amount at the seat as there is no backrest but the feet are rotating with the platform, therefore the relative motion between the torso and the feet decreases with increasing frequency because the rotational displacement decreases. Because there is no backrest, there is no surface to produce fore-and-aft acceleration at the back of the participants and therefore the only mechanisms for discomfort are the acceleration at the seat and the relative motion between the torso and the feet. The centre-of-rotation was centred on the seat surface, causing the acceleration magnitude to be small (nominally zero apart for the gravitational component), because the translational vibration caused by pitch was proportional to the distance from the centre of rotation. As both mechanisms for discomfort are increasingly inefficient with increasing frequency, the energy transfer into the body is low.

In the condition with the backrest, fore-and-aft acceleration at the backrest (due to pitch acceleration of the seat) contributed to discomfort and its importance increased with increasing frequency, relative to the importance of acceleration in the plane of the seat due to gravity. Because the backrest was further from the centre-of-rotation than the seat surface, and the acceleration was normal to the surface of the back, it produced greater acceleration of the torso than the oscillation at the seat surface beneath the ischial tuberosities.

If the rate-of-growth of vibration discomfort differs according to the part of the body primarily excited by vibration, with a greater rate of growth when vibration discomfort is experienced in the central parts of the body, the rate-of-growth of discomfort will be greater in the condition with the backrest. The fore-and-aft acceleration at the backrest was a cause of vibration discomfort in the torso that did not decrease with increasing frequency, so the rate-of-growth of vibration discomfort was greater in the condition with the backrest than without the backrest at frequencies greater than 1.0 Hz, where the discomfort caused by gravity became less important.

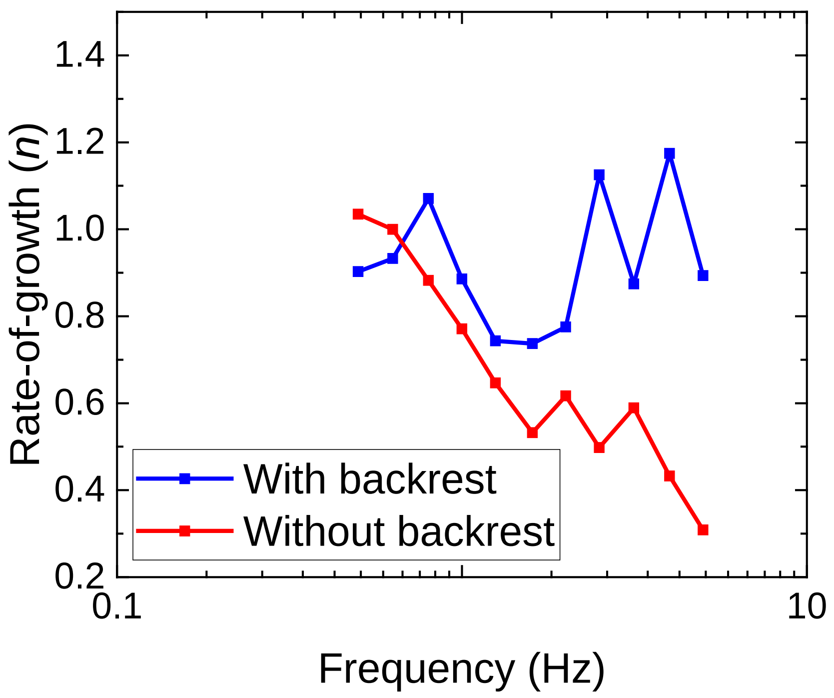

Figure 8.1 Rates-of-growth of discomfort, *n*, for pitch oscillation when sitting with a backrest (blue) and sitting without a backrest (red). Median values and inter-quartile ranges from 15 subjects.

The rate-of-growth of discomfort for pitch oscillation with and without a backrest was investigated by Wyllie and Griffin (2009). It was observed that in the frequency range of 0.2 to 1.6 Hz the rate-of-growth of discomfort was not significantly dependent on the presence of a backrest. This is reasonably similar to the results presented in Chapter 4, where within this frequency range only the rate-of-growth of discomfort at 1.0 Hz differed significantly with and without a backrest. Greater differences in the rate-of-growth of discomfort were observed at frequencies greater than 1.6 Hz, and the location of the body experiencing the vibration differed. In the condition without the backrest at frequencies less than 1.6 Hz, the dominant source of vibration discomfort was felt in the torso and, as in the current study, was probably caused by the acceleration due to gravity. With increasing frequency, the dominant cause of vibration discomfort probably became the acceleration at the interfaces between the seat and body, with a lower rate-of-growth of vibration discomfort, again as in the current study. In the condition with the backrest, the same dominant cause of vibration discomfort existed at frequencies less than 1.6 Hz, but at greater frequencies the dominant cause of vibration discomfort became the motion of the torso caused by vibration at the interface between the backrest and the back. The torso became the body location experiencing the majority of the vibration discomfort and the rate-of-growth of discomfort remained greater than without the backrest as the frequency increased.

This is further supported by the rates-of-growth between the backrest and the seat surface in the fore-and-aft direction. This study suggests that the rate-of-growth of discomfort in the fore-and-aft direction at the back is greater than the rate-of-growth of discomfort in the fore-and-aft direction at the seat at frequencies greater than about 1.25 Hz. Median rates-of-growth for fore-and-aft backrest vibration between 2.0 and 5.0 Hz with a full (0.65 m high) backrest reported by Morioka and Griffin (2010b) and median rates-of-growth of discomfort for fore-and-aft backrest vibration between 2.5 and 5.0 Hz with a full height (0.5 m) backrest at 0° inclination reported by Basri and Griffin (2011b) are consistently greater than the median rates-of-growth for fore-and-aft seat vibration reported in Chapter 6 of this thesis. The concept of the body location determining the rate-of-growth of discomfort is explored further in Section 8.3.1.

8.2.2 Equivalent comfort contours

The influence of the rate of growth of discomfort can be seen in the equivalent comfort contours for pitch oscillation with and without a backrest obtained in Chapter 4 (Figure 8.2).

Without the backrest, a large effect of frequency on the rate of growth of vibration discomfort produces systematic changes in the shapes of the equivalent comfort contours. At frequencies less than 1.25 Hz, the change in acceleration magnitude required to increase discomfort from equivalent levels of 50 to 100 (or 100 to 150) is less than the change in acceleration magnitude necessary for the same increase of discomfort at frequencies of 1.25 Hz and greater (Figure 8.2, red line). With increasing frequency of oscillation, this causes the shapes of the contours to change from no systematic increase in the acceleration necessary to cause equivalent discomfort at low magnitudes, to increasing acceleration necessary to cause equivalent discomfort at high magnitudes.

With the backrest, there is little systematic change in the shapes of the equivalent comfort contours with changing magnitude of vibration, because the rate of growth does not change systematically with increasing frequency.

The differences in the rate of growth of discomfort cause the shapes of the equivalent comfort contours to change at different magnitudes. Consequently, the increase in vibration discomfort caused by the backrest at frequencies greater than about 1 Hz increases with increasing magnitude of vibration as well as increasing frequency of vibration.

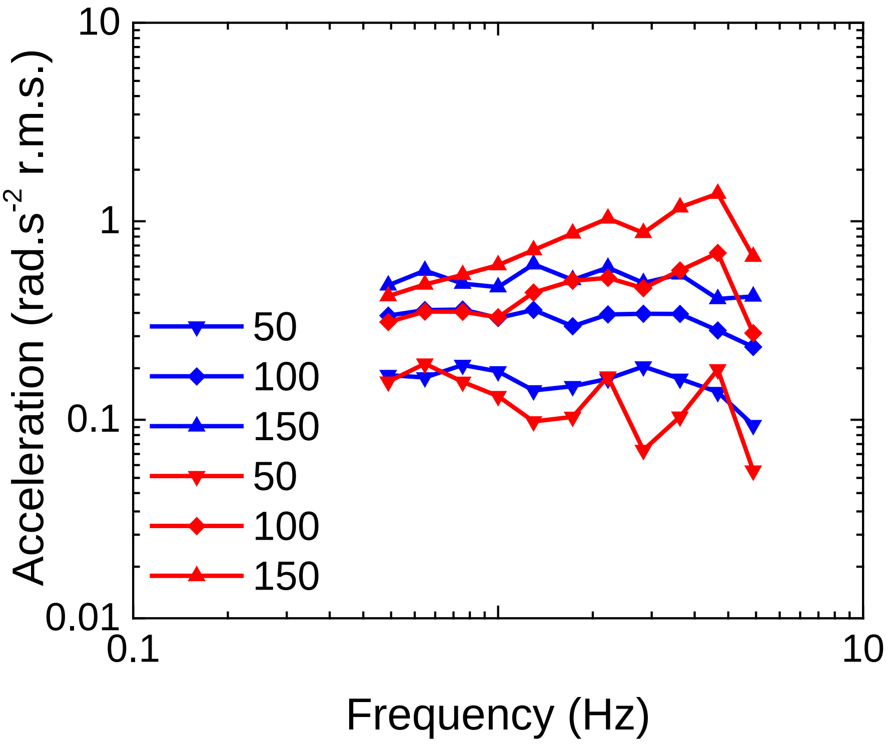

Figure 8.2 Comparison of equivalent comfort contours for a subjective magnitude ψ = 50, 100 and 150 in terms of unweighted r.m.s. pitch acceleration calculated from the median equivalent comfort contours of 15 subjects sitting with (blue) and without (red) a backrest.

8.2.3 Implications of the findings on methods for assessing pitch oscillation

The current British standard BS 6841:1987 advocates measuring vibration in twelve axes to predict vibration discomfort: in all six axes at the seat and in the three translational axes at the backrest and the floor supporting the feet. If these guidelines are followed, the discomfort arising from fore-and-aft vibration at the backrest due to pitch vibration at the seat (or floor) may be predicted from the fore-and-aft vibration at the backrest, and the discomfort caused by the gravitational component at low frequencies may be predicted from pitch oscillation of the seat surface. Figure 8.3 shows reasonable agreement between the discomfort reported in Chapter 4 in the condition with the backrest and the root-sums-of-squares of the W_c and W_e frequency-weighted acceleration found in the British Standard (1987), suggesting that weighted measurements of fore-and-aft acceleration at the backrest and pitch acceleration at the seat provide reasonable predictions of discomfort arising from pitch oscillation.

Because the magnitude of the fore-and-aft acceleration due to pitch oscillation is proportional to the distance from the centre of rotation, the height of the accelerometer on the backrest used in measurements is critical for obtaining a useful estimate of vibration discomfort. For fore-and-aft acceleration at the backrest, Morioka and Griffin (2010) found that the most accurate prediction of discomfort was obtained from the weighted acceleration magnitude measured at the highest point of contact between the human body and the seat surface. By measuring fore-and-aft acceleration at the highest contact point on the backrest, a greater acceleration magnitude will be measured than if a lower position was used, because the distance from the centre-of-rotation is greatest at the highest contact point. This will inherently avoid the possibility of underestimation of fore-and-aft vibration discomfort caused by pitch oscillation in a seat with a backrest.

The position of the axis of rotation on the discomfort of seated subjects was investigated by Parsons and Griffin (1978). It was observed that at frequencies and directions where subjects would normally experience greater discomfort from translational acceleration than rotational acceleration, equivalent comfort contours followed the contour shapes for the translational component of vibration as the distance from the centre-of-rotation increased. The centre-of-rotation for the experiment reported in Chapter 4 was set to the base of the seat, therefore the backrest was not at the centre of rotation and had fore-and-aft motion due to the pitch oscillation at the base of the seat. For discomfort experienced at the back from the backrest, Parsons and Griffin (1978) concluded that either the most severe component (either translational or rotational) or an r.s.s. summation of both components accurately predicted discomfort caused by translational acceleration due to rotation, which is consistent with the r.s.s. of frequency weightings W_c and W_e showing reasonable agreement with the equivalent comfort contour produced by pitch oscillation when sitting with the backrest.

The vibration experienced at the feet of participants will also be affected by the distance from the centre-of-rotation. As the feet were off the axis of rotation in both the *x*-axis and the *z*-axis, pitch rotation centred on the seat surface at the ischial tuberosities will cause fore-and-aft and vertical vibration at the feet. The standardised frequency weighting given to vibration discomfort in these two axes at the feet is W_b, suggesting that the feet are relatively insensitive to vibration at low frequencies and peak in sensitivity around 5 Hz to 16 Hz. This may contribute to the increase in sensitivity at 5 Hz seen in the condition without the backrest in Figure 8.2 (red lines). Parsons *et al.* (1982) found greater sensitivity to low frequency motion at the feet than frequency weighting W_b suggests, however the experiment was performed with a stationary seat and therefore the increased sensitivity at low frequencies may be due partially to the relative displacement between the seat and the feet, which did not occur in the experiment presented in Chapter 4.

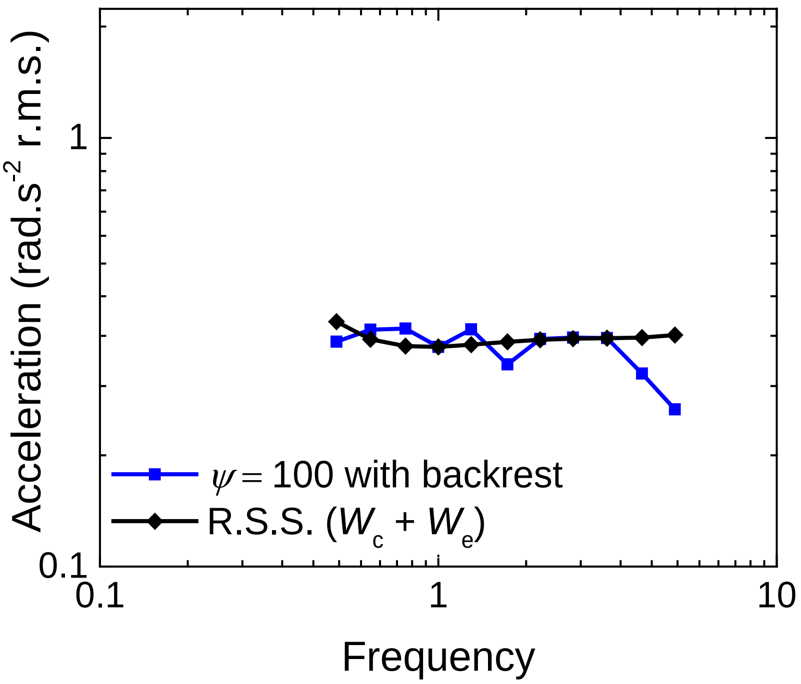

Figure 8.3 Comparisons of equivalent comfort contours for ψ = 100 in terms of unweighted r.m.s. pitch acceleration and inverted frequency weighting from BS 6841 (1987). Comparison between the condition with the backrest in Chapter 4 and an r.s.s. of W_c and W_e. The reciprocal of the frequency weighting curve is normalised to be equal to the equivalent comfort contour at 1 Hz.

It can be common practice not to measure vibration at the seat surface or the backrest and instead only measure translational vibration at the floor of a vehicle. If pitch oscillation is not measured at the floor, the discomfort caused by pitch oscillation will not be accounted for. Where it is impractical to measure fore-and-aft vibration at the backrest, discomfort may be predicted if pitch oscillation is measured at the seat or the floor of the vehicle, although the dynamic response of the seat would need to be known to make good predictions for non-rigid seats.

8.3 Effect of magnitude of vibration on the frequency-dependence and inter-axis equivalence of subjective response to translational vibration

8.3.1 Rate of growth of discomfort

A main message from this thesis concerns the influence of the rate-of-growth of discomfort on the prediction of vibration discomfort. The rate-of-growth of discomfort affects the human sensitivity to each frequency and axis of vibration. So unless the rate-of-growth of discomfort is the same at all frequencies and in all axes of vibration, a single frequency weighting and a single axis multiplying factor for each axis and location of vibration will be insufficient to predict vibration discomfort across a range of magnitudes.

The sensitivity between axes, the ‘inter-axis equivalence’, of vibration discomfort (Section 8.3.3) differs at different magnitudes. If the experienced inter-axis equivalence of discomfort is different from the inter-axis equivalence provided in the evaluation techniques of BS 6841:1987 or ISO 2631-1:1997, the dominant axis of vibration causing discomfort may not be that measured and evaluated as the greatest magnitude vibration input to the body.

In the frequency range 1.0 to 10 Hz, it was seen in Chapter 6 that the rate-of-growth of discomfort significantly depended on the frequency of the vibration. In the fore-and-aft and lateral axes there were clear peaks in the rate-of-growth of discomfort: at 2.5 Hz in the fore-and-aft axis and at 1.6 Hz in the lateral axis (Figure 8.4). Above and below these frequencies, the rate-of-growth of discomfort decreased with increasing and decreasing frequency, respectively. In the vertical axis, there was also a significant difference in the rate-of-growth of discomfort across the frequency range studied, generally decreasing with increasing frequency. However, the percentage difference in the rate-of-growth of discomfort across the range of 1.0 to 10 Hz was less than in both horizontal axes.

There are a several possible mechanisms behind the variations in rates-of-growth of vibration discomfort. The local peak found in the results from the fore-and-aft and lateral vibration occurred at a similar frequency to the second mode resonances in the seated human biodynamic response to fore-and-aft and lateral vibration reported by Fairley and Griffin (1990). Another possible cause of the peaks found in the fore-and-aft and lateral results is the nonlinearity of the biodynamic response due to vibration magnitude as observed by Matsumoto and Griffin (2005) and Subashi *et al.* (2009). If biodynamic resonance causes increased discomfort from vibration, and the frequency of the resonance decreases with increasing magnitude, it is reasonable to expect the rate-of-growth of discomfort to be high at frequencies where the resonance is not present at low magnitude but is present at high magnitude. Figure 8.5 shows the median apparent mass of 12 participants measured in the fore-and-aft direction by Subashi *et al.* (2009).

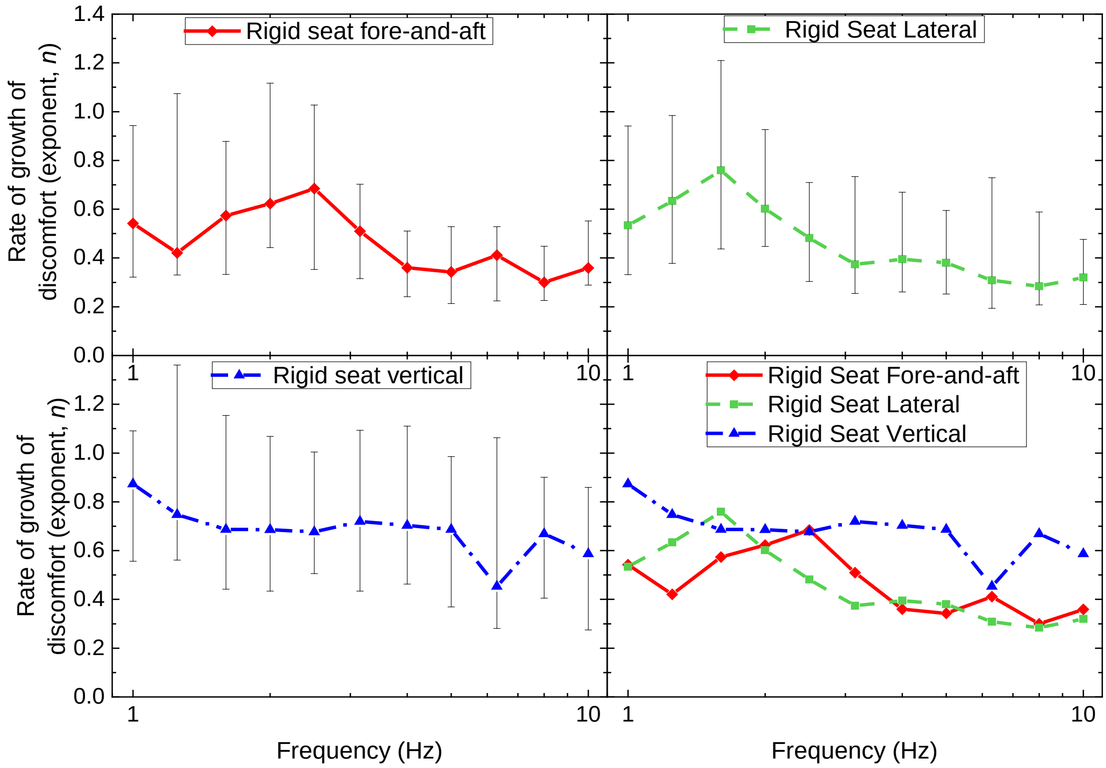

Figure 8.4 Rates of growth of vibration discomfort, *n*, for fore-and-aft vibration (top left), lateral vibration (top right), and vertical vibration (bottom left), and all three directions of vibration (bottom right) when sitting on a rigid seat without a backrest. Medians and inter-quartile ranges for 24 subjects.

It can be seen that with increasing magnitude of vibration, within the magnitude range of 0.125 ms^{-2} to 1.0 ms^{-2} r.m.s., there is an increase in the apparent mass with decreasing frequency and that the peak in the apparent mass decreases in frequency. The greatest increase in apparent mass with increasing magnitude occurs around 2.0 – 2.5 Hz which is similar to the peak rate-of-growth observed in Chapter 6 (unfortunately the data from Subashi *et al.* (2009) do not include apparent mass from the 1.0 ms^{-2} r.m.s. at frequencies less than 3.15 Hz). At 4.0 Hz and above, the apparent mass decreases with increasing vibration magnitude. This may account for the low rate-of-growth of discomfort with increasing frequency as the force between the seat surface and the human body reduces with increasing acceleration, assuming that force between the seat surface and the human influences the vibration discomfort experienced.

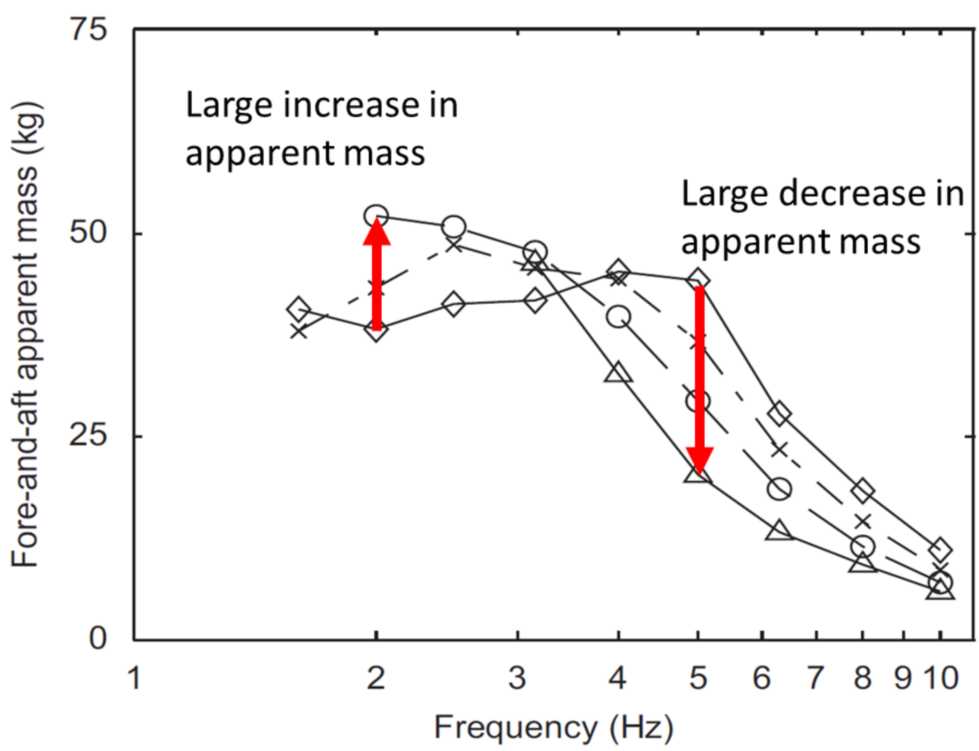

Figure 8.5 Median apparent mass of 12 subjects exposed to fore-and-aft vibration at four magnitudes: ◊ - : 0.125 ms^{-2} r.m.s.; ×-.-.-.: 0.25ms^{-2} r.m.s.; o- - - -: 0.5 ms^{-2} r.m.s.; Δ - : 1.0 ms^{-2} r.m.s. From figure 3 Subashi *et al.* (2009).

The discomfort from fore-and-aft motion reported by Subashi *et al.* (2009) showed a similar trend to the biodynamic response to fore-and-aft motion (Figure 8.6). Vibrations at four magnitudes (0.125, 0.25, 0.5, and 1.0 ms^{-2} r.m.s.) at each preferred one-third octave centre frequency from 1.6 Hz to 10 Hz using the method of constant stimuli where the reference for each pair of motions was a 4.0 Hz sinusoid at the same unweighted magnitude as the test vibration. At frequencies less than 4.0 Hz, the discomfort relative to the reference increased with increasing magnitude (except at 3.15 Hz where the relative discomfort of the 0.5 ms^{-2} vibration was greater than the relative discomfort of the 1.0 ms^{-2} vibration). At 5.0 Hz, close to the peak in apparent mass of the 0.125 ms^{-2} vibration, relative discomfort decreased with increasing magnitude. This finding suggests that at these frequencies vibration discomfort and the biodynamic response of the human body are linked and this supports the idea that the change in the resonance frequency of the biodynamic response of the body affects the rate-of-growth of discomfort.

In Section 8.2.1 it was briefly discussed that a greater rate-of-growth-of discomfort may be experienced when the greatest vibration discomfort is felt in the more central parts of the body (torso). Figure 8.7 shows the locations of discomfort for fore-and-aft, lateral, and vertical whole-body vibration. With the fore-and-aft excitation, there was a significant reduction in the dominance of vibration discomfort in the lower and upper torso as the frequency increased. This is consistent with vibration discomfort in the central parts of the body increasing the rate-of-growth of discomfort, because the rate-of-growth of discomfort decreased with increasing frequency at frequencies greater than 2.5 Hz. Whilst there was no statistically significant difference in the reported vibration discomfort in the torso with lateral excitation, with increasing frequency it is possible to see that the torso was generally reported less as a location of greatest discomfort with increasing frequency.

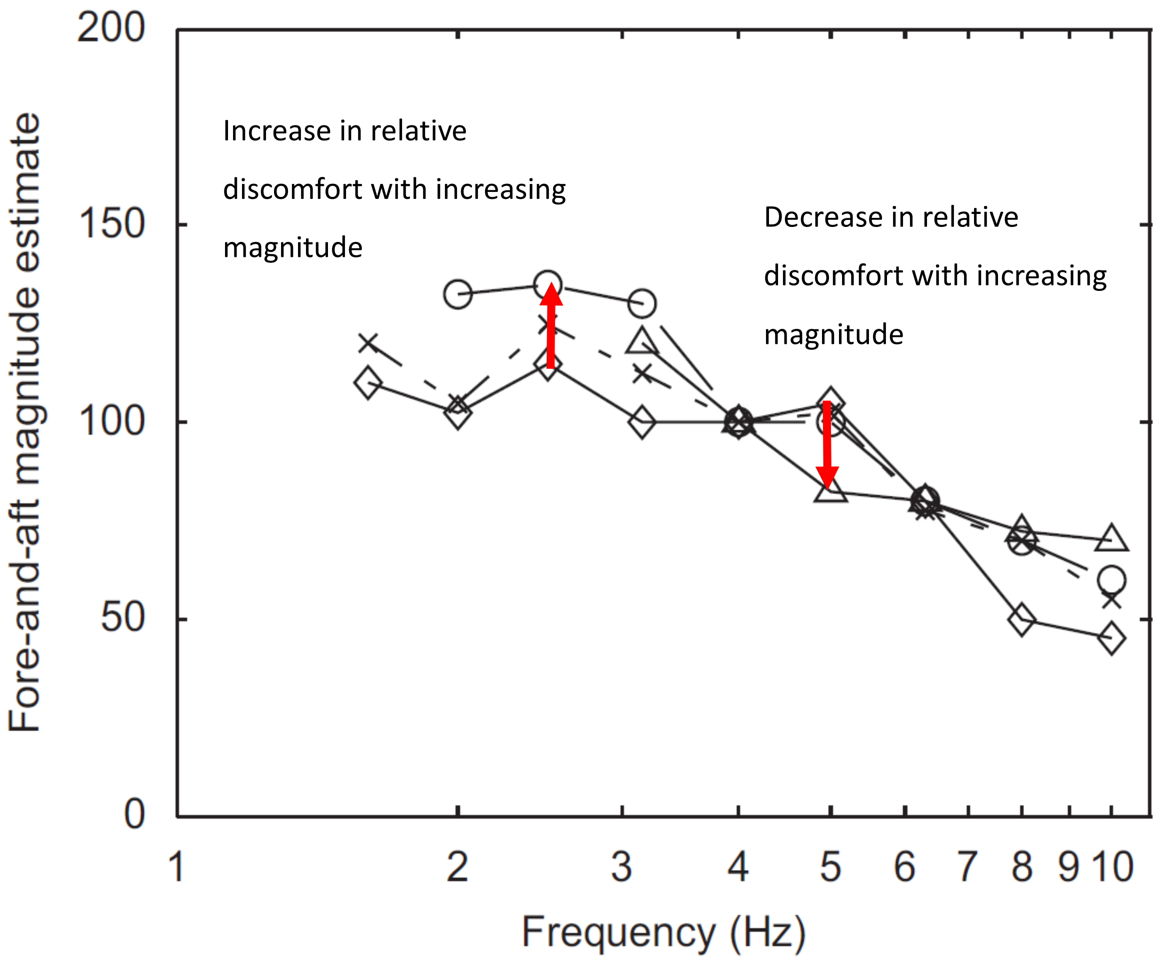

Figure 8.6 Median magnitude estimates of relative discomfort by 12 subjects exposed to fore-and-aft vibration at four magnitudes: ◊ - : 0.125 ms^{-2} r.m.s.; ×-.-.-.: 0.25ms^{-2} r.m.s.; o- - - -: 0.5 ms^{-2} r.m.s.; Δ - : 1.0 ms^{-2} r.m.s. From figure 2 Subashi *et al.* (2009).

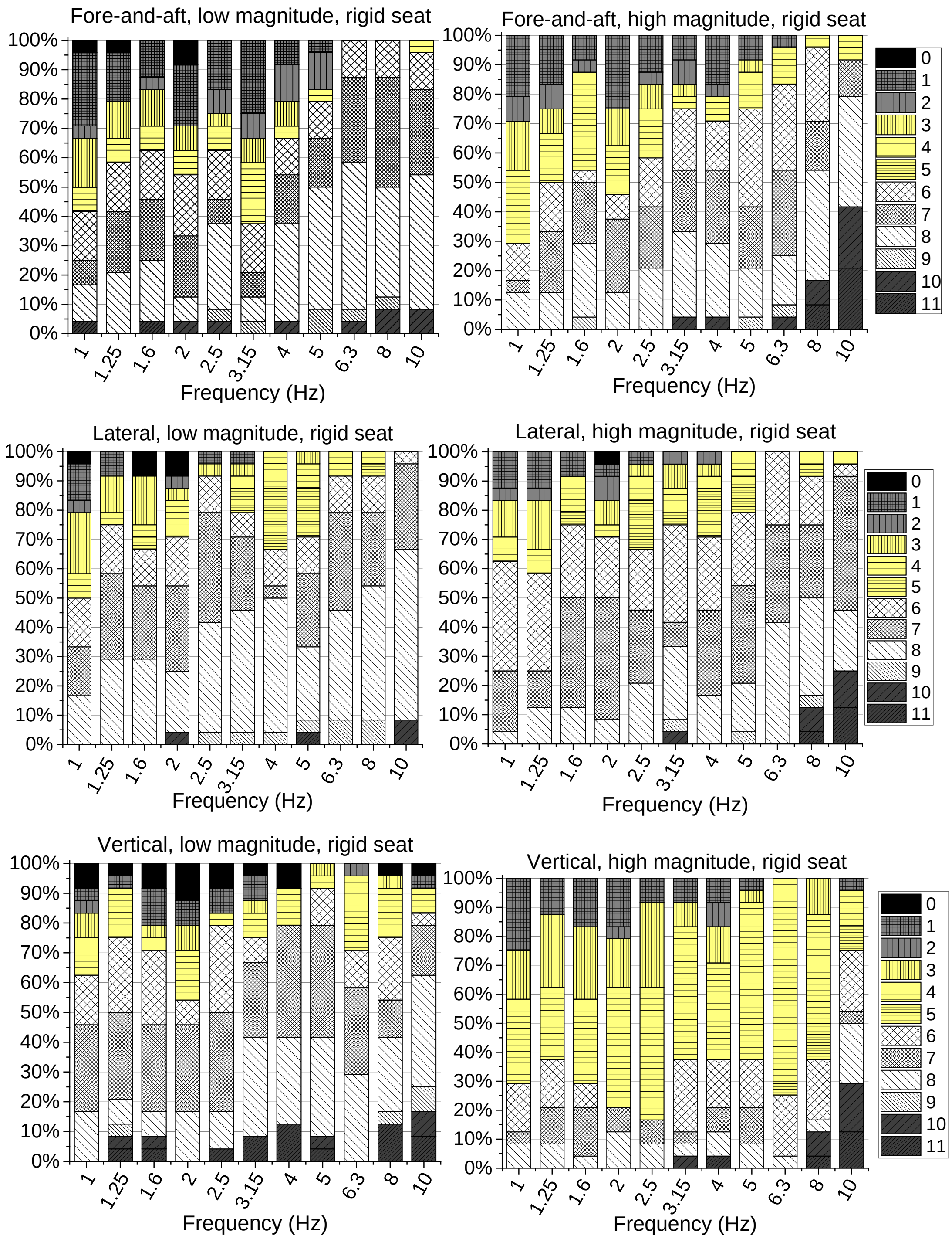

Figure 8.7 Reported body locations of most discomfort in each axis of vibration, at 'low' magnitudes (0.088 ms^{-2} r.m.s., weighted) and 'high' magnitudes (0.70 ms^{-2} r.m.s., weighted) with a rigid seat. Body locations – 0: 'no discernible location'; 1: head; 2: neck; 3: shoulders; 4: chest; 5: arms; 6: lower abdomen; 7: ischial tuberosities, 8: lower thighs; 9: upper thighs; 10: legs; and 11: feet.

From the evidence above, it is reasonable to suggest that two major contributors to the rate-of-growth of discomfort are changes in the apparent mass of the human body with increasing vibration magnitude due to the nonlinear biodynamic response of the human body, and changes in the location of greatest discomfort during whole-body vibration in different directions and different frequencies. At frequencies and in axes where the apparent mass of the human body increases with increasing magnitude, the rate-of-growth of discomfort will be greater. At frequencies and in axes where the location of greatest discomfort is in the central parts of the body, the rate-of-growth of discomfort will also be greater, and at frequencies and in axes where the location of greatest discomfort is restricted to the extremities of the body, the rate-of-growth of discomfort will be less.

The graphs presented in Figure 8.8 show some similarities and differences in the rate-of-growth of discomfort between the study shown in Chapter 6 and previous research (Morioka and Griffin, 2006; Wyllie and Griffin, 2007, 2009; Basri and Griffin, 2012; Zhou and Griffin, 2014).

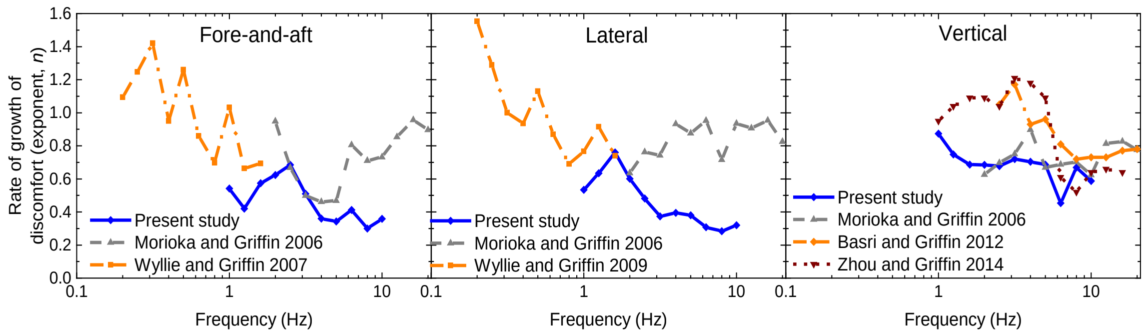

Figure 8.8 Rates of growth of vibration discomfort, *n*, for fore-and-aft, lateral, and vertical whole-body vibration for a rigid seat without a backrest. Present study (blue) Morioka and Griffin (2006a) (grey), Wyllie and Griffin (2007) (orange, fore-and-aft), Wyllie and Griffin (2009) (orange, lateral), Basri and Griffin (2014) (orange, vertical) and Zhou and Griffin (red, vertical).

The previous studies have used different seating conditions (flat or contoured to fit the contours of the body (e.g., a saddle)), different footrest conditions (stationary or moving), different types of magnitude estimation (absolute magnitude estimation or relative magnitude estimation), and differed in whether or not the eyes of the subjects were open or closed. Some of these factors may be causing some of the differences seen in the rates-of-growth of discomfort. Future studies should investigate how seating conditions and external triggers affect the rate-of-growth of discomfort during vibration exposure in addition to the effects of the direction and frequency of vibration.

The rate-of-growth of discomfort is dependent on both the frequency and the direction of vibration and therefore influences the frequency-dependence of equivalent comfort contours at different magnitudes and the inter-axis equivalence of vibration discomfort.

8.3.2 Equivalent comfort contours

Figure 8.9 shows the equivalent comfort contours for fore-and-aft, lateral and vertical vibration at subjective magnitude estimates from ψ = 63 to ψ = 160 (where ψ = 100 is equivalent to the discomfort caused by 3.15 Hz vertical vibration at 0.25 ms^{-2} r.m.s., weighted, 0.38ms^{-2}, unweighted).

The effect of the rate-of-growth of discomfort, especially in the horizontal axes, can be seen from the curves shown in Figure 8.9. It can be seen that at low magnitudes, similar vibration discomfort is experienced at similar magnitudes in the fore-and-aft and lateral axes across the range of 1.0 to 10 Hz. With increasing magnitude, the sensitivity to vibration discomfort reduces with increasing frequency.

Equivalent comfort contours in the vertical direction remain relatively parallel throughout the magnitude range investigated in Chapter 6 (Figure 8.9) because the percentage change in the rate-of-growth of discomfort is relatively small over the range of frequencies investigated. The exception to this is at 6.3 Hz where the rate-of-growth is less than over the rest of the frequency range chosen. Whilst there is a general trend for the rate-of-growth to decrease with increasing frequency, the difference is quite small when compared to the changes in the fore-and-aft and lateral directions and this is reflected in a less dramatic change in the shapes of the equivalent comfort contour across the magnitude range shown.

8.3.3 Inter-axis equivalence of vibration discomfort

The British and International Standards (BS 6841:1987 and ISO 2631-1:1997) show a single frequency weighting curve for horizontal vibration discomfort (W_d) and a single curve for vertical vibration discomfort (W_b (BS 6841:1987) and W_k (ISO 2631-1:1997)). This implies not only that the frequency dependence on discomfort is not affected by the magnitude of vibration, but also that relative frequency dependence of discomfort between axes does not depend on the magnitude of the vibration.

When using the W_b and W_d curves as advocated in the British Standard to evaluate vibration with respect to discomfort, the discomfort caused by a vibration of the same magnitude is considered equivalent between the horizontal and vertical axes at 3.15 Hz. At frequencies less than 3.15 Hz, horizontal vibration is considered more uncomfortable than vertical vibration, and at frequencies greater than 3.15 Hz vertical vibration is considered more uncomfortable than horizontal vibration. Figure 8.10 shows the reciprocals of the W_b and W_d frequency weighting curves at different magnitudes (reciprocals of frequency weighting curves can be considered similar to equivalent comfort contours, assuming the weighting curve accurately reflects human discomfort from vibration). It can be seen that the frequency weighting curves remain parallel and that the crossover frequency between horizontal (red) motion causing greatest discomfort and vertical (blue) motion causing greatest discomfort is 3.15 Hz at all magnitudes of vibration.

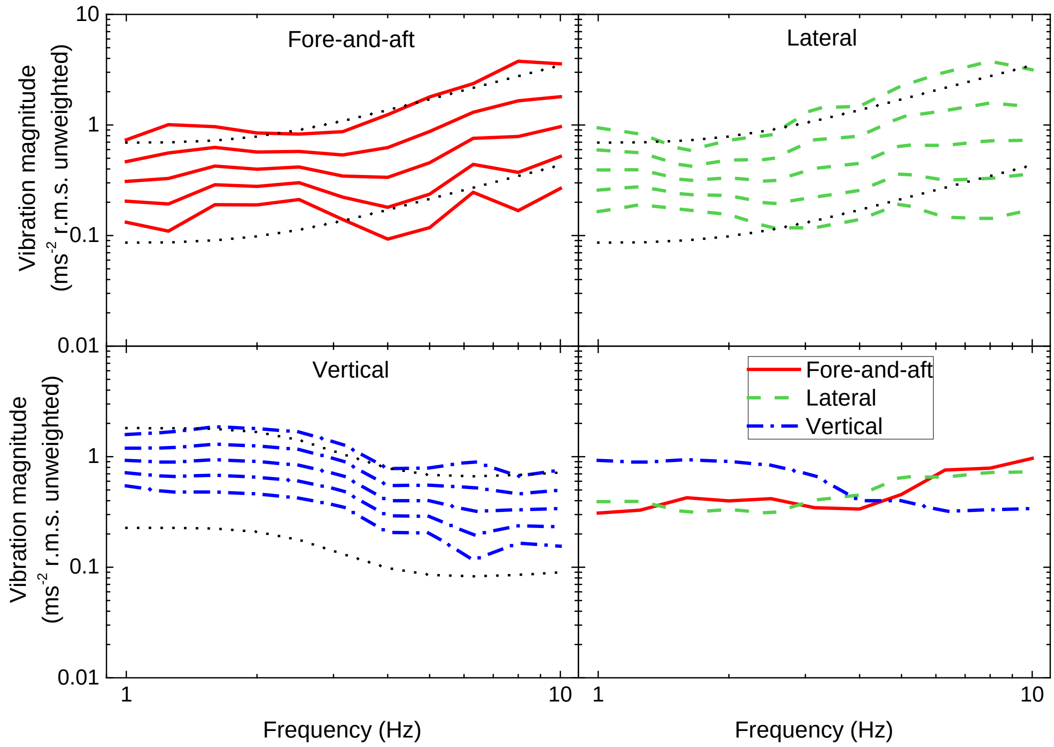

Figure 8.9 Equivalent comfort contours for fore-and-aft, lateral and vertical vibration for subjective magnitudes from 63 to 160 relative to 0.25 ms^{-2} vertical vibration at 3.15 Hz. Ranges of stimuli employed in the study shown by dotted lines (….). Bottom right graph compares equivalent comfort contours between the three directions for a subjective magnitude of 100.

Figure 8.11 shows pairs of equivalent comfort contours produced in Chapter 6, comparing fore-and-aft vibration with vertical vibration, comparing lateral with vertical vibration, and comparing fore-and-aft with lateral vibration (at subjective magnitudes of ψ = 63, 80, 100, 125, and 160, where ψ = 100 is equivalent to the discomfort caused by 3.15 Hz vertical vibration at 0.25 ms^{-2} r.m.s., weighted, 0.38 ms^{-2} r.m.s., unweighted). The crossover frequencies are highlighted with circles, it is clear from comparisons between the fore-and-aft and vertical equivalent comfort contours, and between the lateral and vertical equivalent comfort contours that, at low magnitudes there is a greater sensitivity to horizontal vibration than vertical vibration at frequencies greater than 3.15 Hz. With increasing magnitude of vibration, the frequency at which vertical vibration causes greater discomfort than horizontal vibration decreases. This finding also suggests that horizontal vibration will become a dominant source of vibration discomfort at frequencies greater than 3.15 Hz at low magnitude.

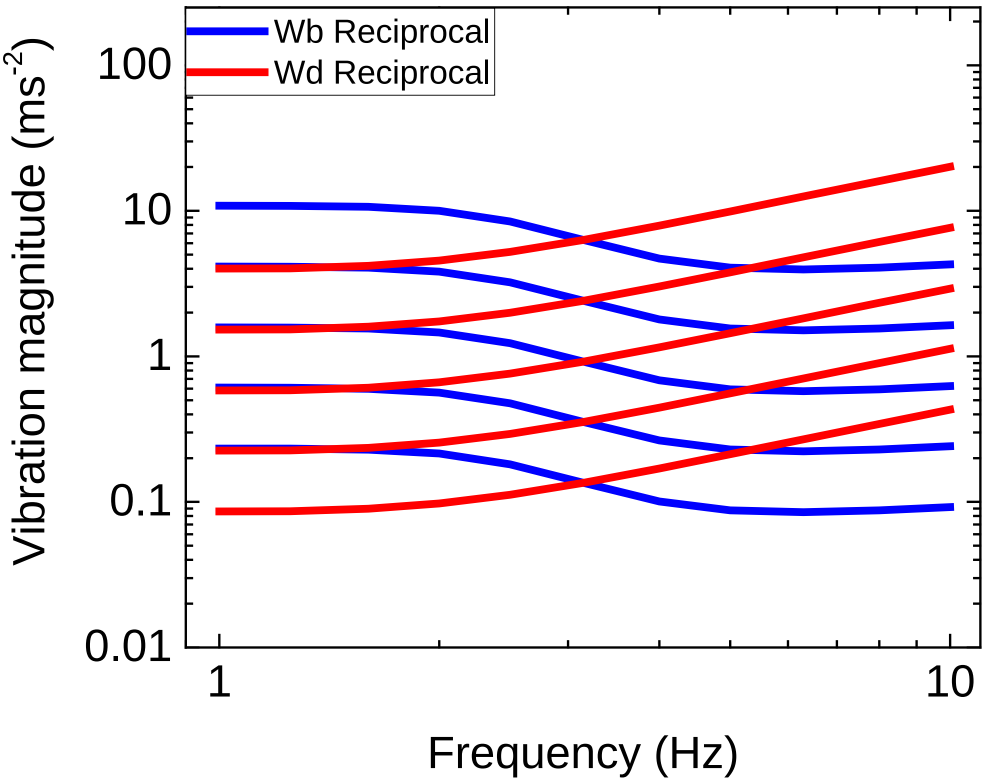

Figure 8.10 Reciprocals of W_b and W_d frequency weightings from BS 6841 (1987) at different equivalent magnitudes showing the same crossover frequency of 3.15 Hz.

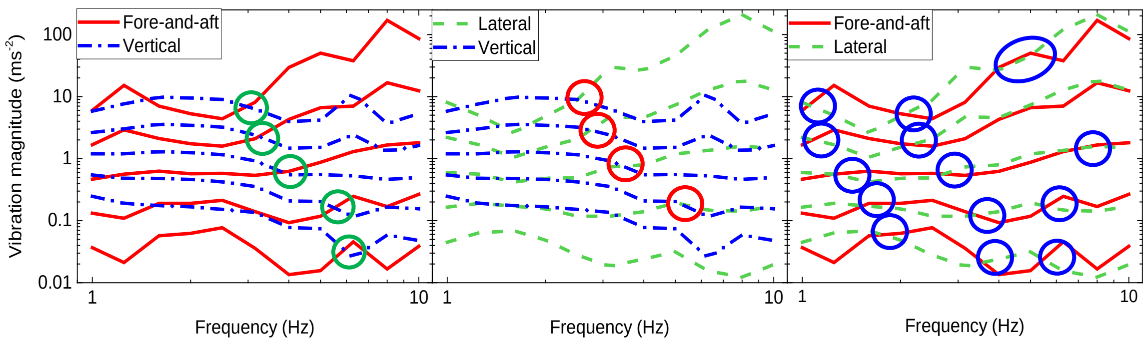

Figure 8.11 Comparisons of equivalent comfort contours between axes for subjective magnitudes from 63 to 160 in the fore-and-aft (red), lateral (green) and vertical (blue) directions, relative to a vibration magnitude of 0.25 ms^{-2} vertical vibration at 3.15 Hz. Without beanbag. Circles show systematic changes in the frequencies of the cross-overs between pairs of equivalent comfort contours in different axes. Median data from 24 subjects.

8.3.4 Implications of the findings on methods for evaluating translational vibration with respect to vibration discomfort

Current British and International standards advocate single frequency weighting curves and single axis multiplying factors (unity for translational vibrations at the seat when evaluating vibration to predict discomfort) for each direction of vibration irrespective of the vibration magnitude. The results presented in Chapter 6 show that a single frequency weighting curve is inappropriate at vibration magnitudes very different from those used during the initial studies that influenced the frequency weighting curves present in the standards (Griffin *et al.,* 1982a), because the rate-of-growth of discomfort changes the shapes of the equivalent comfort contours with increasing and decreasing magnitude. In addition to this, because of differences in the rate-of-growth of discomfort across different frequencies and directions, the inter-axis equivalence of human sensitivity to vibration discomfort changes with the magnitude of vibration. Current evaluation techniques will underestimate sensitivity to horizontal vibration at frequencies greater than 3.15 Hz at low magnitude when compared with sensitivity to vertical vibration at frequencies greater than 3.15 Hz at low magnitude. With increasing magnitude, the importance of the vertical axis of vibration relative to the horizontal axes of vibration increases at frequencies above 3.15 Hz.

It might be proposed that new nonlinear frequency weightings could be created to incorporate the rate-of-growth of discomfort to reflect more accurately human sensitivity to vibration across different frequencies, magnitudes, and directions. However, this would be complicated from a signal processing perspective and difficult for users of frequency weightings to understand. A simpler compromise solution may be to have a few different weightings and axis multiplying factors for different ranges of vibration magnitude, similar to the field of acoustics having both the A-weighting and C-weighting frequency curves.

8.4 Effect of frequency and direction on subjective response to multi-frequency and multi-axis vibration

8.4.1 The importance of rate-of-growth when predicting discomfort caused by multi-axis vibration.

The results in Chapter 7 show that the median rate-of-growth of discomfort for each axis and frequency of tri-axial vibration were correlated with the optimum value of the power α used to predict tri-axial vibration discomfort from each component in the tri-axial motion. The reason behind this may be similar to how the rate-of-growth affects single-frequency single-axis vibration discomfort. The rate-of-growth dictates the increased sensation experienced with increasing magnitude of the stimulus, in this case vibration. When a vibration doubled in magnitude, the increased discomfort experienced is directly related to the rate-of-growth of discomfort, *n*. If *n* is equal to 1.0, the discomfort will double, if *n* is less than 1.0 the discomfort will increase by less than double and if *n* is greater than 1.0 the discomfort will increase by more than double. It is reasonable to assume that the same may apply to multi-axis vibration. Assume two vibrations in separate axes cause the same subjective magnitude of discomfort as each other when experienced separately and have the same rate-of-growth of discomfort. It would seem reasonable to assume that the increase in the subjective magnitude experienced when the two vibrations are combined would be the same as if one of the vibrations had doubled in magnitude, with the increase in discomfort determined by the rate-of-growth of discomfort.

If the subjective magnitude of two orthogonal axes of vibration could be predicted by the linear sum of magnitude estimates, augmented by the rate-of-growth of discomfort, then the discomfort produced by a dual axis vibration, where the magnitude estimate and the rate-of-growth in each axis is the same, would equal the discomfort experienced by one of the axes doubling in acceleration. However, previous studies suggest that the discomfort caused by two axes of vibration is poorly predicted by the linear sum of the two physical components. From the results of experiments investigating the prediction of discomfort caused by dual-axis vibration (Fairley and Griffin, 1988; Mistrot *et* al., 1990) this assumption may be considered inappropriate. It may be better to assume that the discomfort caused by multi-axis vibration is summed 'in the brain' in a way that can be predicted by a power summation, with the rate-of-growth of vibration discomfort affecting the discomfort experienced. If the power in the power summation method to predict multi-axis vibration discomfort is considered α and the rate-of-growth of discomfort is considered as *n*, this may be written as:

$$\psi_{total} = \left(\psi_x^{n_x\alpha} + \psi_y^{n_y\alpha} + \psi_z^{n_z\alpha}\right)^{1/n_i\alpha} \tag{8.1}$$

where ψ is the magnitude estimate of vibration discomfort (i.e., quantified on a ratio scale) for the tri-axial vibration, and the fore-and-aft, lateral, and vertical components of the tri-axial vibration, with subscripts *total*, *x*, *y*, and *z* respectively; *n* is the rate-of-growth of vibration discomfort for the tri-axial vibration, and the fore-and-aft, lateral, and vertical components of the tri-axial vibration with subscripts *x*, *y*, *z*, and *i* respectively; α is the power for summation of the discomfort caused by orthogonal axes of vibration 'in the brain'.

Equation 8.1 may be considered an idealised model for predicting the discomfort caused by multi-axis vibration, but there are some caveats. If n_x, n_y and n_z are equal it might be assumed that n_i

has the same value as n_x, n_y and n_z. However, the results presented in Chapter 6 have shown that the rate of growth of vibration discomfort can be very different for the three components in a tri-axial vibration and it is then not obvious how to calculate a value for n_i. As the three values for n_x, n_y and n_z become more different it is likely that the wrong choice for n_i becomes more critical. The investigation presented in Chapter 7 did not provide sufficient information to determine how to calculate a common rate-of-growth, n_i, to be used in Equation 8.1.

The rate-of-growth of discomfort and the optimum power used in a power summation to predict tri-axial discomfort are correlated and the first paragraph of this sub-section reasons why this might be assumed to be a causal relationship. A model to predict discomfort from tri-axial vibration that incorporates the rate-of-growth of discomfort is given by Equation 8.1, although there are limitations and unknown factors in that model. Further investigation is required to understand the relationship between the rate-of-growth of discomfort in individual axes of vibration and how these can be used to form a global rate-of-growth of discomfort to be used in Equation 8.1.

8.4.2 Implications of the findings on methods for assessing multi-axis vibration discomfort

The choice of using a power of 2 (root-sums-of-squares, r.s.s.) for summing objective measurements of vibration is consistent with the findings of investigations by Fairley and Griffin (1988) and Mistrot *et al.* (1990). Using the method of constant stimuli, dual-axis sinusoidal and dual-axis one-third octave random vibration discomfort was reasonably well predicted using the r.s.s. method, with the worst component and linear sum performing relatively poorly.

The r.s.q. method of predicting multi-axis vibration discomfort from objectively measured acceleration has been seen to underestimate discomfort caused by multi-axis vibration (Mistrot *et al.,* 1990). However, the discomfort caused by motions with occasional shocks have been shown to be better predicted when using fourth-power methods (e.g., Griffin, 1990). Errors obtained using the fourth-power method for predicting discomfort from subjectively assessed multi-axis vibration in Chapter 7 were similar to errors obtained using a second-power method, therefore it may be reasonable for the r.s.q. method to be used to evaluate tri-axial motions with occasional shocks. A future experiment could be designed to investigate differing ratios of shock within random vibration (by varying the r.m.s. to r.m.q. ratio) to investigate whether an r.s.q. power summation is a better predictor of multi-axis vibration discomfort above a certain r.m.s. to r.m.q. ratio (or 'crest factor').

Considering the above, it seems reasonable to use the current r.s.s. method where a single 'overall ride value' is required for a motion without noticeable shocks, supported by 'component ride values' for each of the twelve location and axis combinations advocated in BS 6841 (1987). Due to the similarity of the error between the r.m.s. and r.m.q. methods when predicting discomfort from tri-axial vibration, and the advocacy of using a fourth-power method for motions containing shocks, the r.s.q. method should be used for multi-axis motions containing shocks. Investigation into the rate-of-growth of discomfort for single-axis, dual-axis, and tri-axial random vibration is required (similar to Chapter 6 but with random and multi-axis motion). If the rates-of-growth are known for these motions, the rate-of-growth between sinusoidal and random motion may be directly compared. In addition, the rate-of-growth for multi-axis vibration discomfort may give some indication of how n_i (in Equation 8.1) may be determined. This is especially true if there is strong correlation and a causal relationship between the rate-of-growth of discomfort of multi-axis vibration and the rate-of-growth of discomfort of single-axis vibration. Greater understanding of the role of the rate-of-growth of discomfort in predicting multi-axis vibration discomfort would come from this experimentation.

8.5 Practical limitations

There are practical limitations to how much standardised methods for predicting and evaluating vibration discomfort can implement the findings of research on vibration discomfort. This thesis has demonstrated the importance of the rate-of-growth of vibration discomfort when predicting discomfort for single-frequency single-axis motion, whether a backrest is present or not, and when predicting multi-frequency multi-axis vibration discomfort. There are many factors that affect whole-body vibration discomfort such as: direction, duration, frequency, magnitude, phase between vibration inputs, rate-of-growth, crest factors, backrest, backrest inclination, static comfort, posture, location of vibration input, input contact area, etc. It may not be practical to provide a global method for accurately predicting vibration discomfort due to the extraordinary number of factors that affect the discomfort experienced during whole-body vibration. Nevertheless, understanding the role of the rate-of-growth of vibration discomfort as studied in this thesis can help support engineering decisions in the reduction of vibration discomfort even without a universal standardised vibration discomfort evaluation method.

Chapter 9 Conclusions and recommendations

9.1 Conclusions

The discomfort caused by pitch oscillation of a seat at frequencies greater than 1.0 Hz is greater with the presence of a backrest. At frequencies less than 1.0 Hz, the discomfort caused by pitch oscillation of a seat is similar with or without a backrest. The frequency-dependence of vibration discomfort caused by pitch oscillation with the presence of a backrest can be predicted from the pitch acceleration at the ischial tuberosities combined with the fore-and-aft acceleration at the backrest caused by the pitch oscillation.

The magnitude-dependence of the frequency-dependence of vibration discomfort is governed by the rate-of-growth of discomfort. The rate-of-growth of discomfort in the fore-and-aft, lateral, and vertical directions is highly dependent on the frequency and direction of the vibration. Equivalent comfort contours for fore-and-aft and lateral vibration show similar sensitivity to acceleration across the frequency range 1.0 to 10 Hz at low magnitude, at high magnitude there is decreasing sensitivity to acceleration with increasing frequency. In the vertical direction, there is less percentage change in the decrease in the rate-of-growth of discomfort with increasing frequency and the shape of the equivalent comfort contours does not change much over the frequency range studied.

At low magnitudes, people have greater sensitivity to fore-and-aft and lateral vibration than to vertical vibration at frequencies greater than 3.15 Hz, which is the cross-over frequency above which current standards suggest greater sensitivity to vertical vibration than horizontal vibration. With increasing magnitude of vibration, the cross-over frequency decreases as sensitivity to horizontal vibration decreases relative to sensitivity to vertical vibration.

The average rate-of-growth of discomfort caused by single-axis components of octave-band random vibration is highly correlated with the optimal power for summing tri-axial components to predict the discomfort caused by tri-axial vibration from the subjective magnitude of the three components in the motion. This suggests the discomfort caused by tri-axial vibration is dependent on the rate-of-growth of discomfort of vibration at the frequencies and directions present in the vibration. Due to this dependence on the rate-of-growth of discomfort, a single power in the power summation of each axis of multi-axis vibration cannot accurately predict the discomfort caused by multi-axis vibration and an allowance for the rate-of-growth is required for accurate prediction of the discomfort caused by multi-axis vibration.

9.2 Recommendations for further research

Before the construction of magnitude dependent frequency weightings, future studies should determine the relationship between the rate-of-growth of sinusoidal motions and broadband motions by determining the rates of growth at differing bandwidths of frequency in each direction (e.g., 1/3rd octave, octave, 3-octave). This would allow the power of the rate-of-growth can be applied to motions more likely to be experienced in the real world (i.e., non-sinusoidal motions).

To enable more accurate prediction methods of multi-axis vibration discomfort, an investigation into the applicability of Equation 8.1 suggested in Chapter 8 should be carried out. An experiment similar to that presented in Chapter 7 but performed at multiple magnitudes would allow for the mapping of the rate-of-growth of octave-band random vibration and multi-axis random vibration. This will allow for the value of n_i in Equation 8.1 to be calculated and produce a method to predict discomfort due to multi-axis vibration with greater accuracy.

An extension of the above recommendation would be to use motions with differing r.m.s. to r.m.q. ratios to evaluate whether the value of n_i in Equation 8.1 is dependent on transients within the waveform again allowing for more accurate predictions of multi-axis vibration with occasional shocks present.

To discover whether there is a causal relationship between the biodynamic response of the human body and the rate-of-growth of discomfort, an investigation that measures changes in both magnitude estimates of vibration discomfort and biodynamic responses when the biodynamic response is altered during exposure to a single vibration (e.g., restricting movement of the torso during vertical vibration, increasing movement of the torso during horizontal vibration, stabilising the body to control the apparent mass) may be allow this idea to be confirmed or rejected. Understanding the mechanisms behind the variations in the rate-of-growth of discomfort could allow substantial improvements in the predication of discomfort in transport.

Appendices

Appendix A Instructions for participants

A.1 Experiment presented in Chapter 4

INSTRUCTIONS

This experiment is designed to understand your impression of discomfort caused by pitch vibration with different magnitudes and directions.

You will be presented with a series of vibration stimuli.

Please read **carefully** and follow the instructions below.

Preparation:

1. **Practice**

- You will be given a brief practice session so as to familiarise you with the stimuli and the procedure before commencing the main experiment. Ask questions if you are unsure.
- During the practice please sit comfortably on the seat. Rest your hands on your lap.
- Wear the pair of headphones and close your eyes.
- **The experimenter will help you to adjust your seat belt. Please, keep your belt fastened and do not touch it during the experiment.**
- Please maintain the same body posture during the entire duration of the exposure.
- After each motion you will be asked to rate the discomfort.
- The first motion experienced during the practice will be your "reference" for all the rest of the experiment.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

2. **Test**

- You will be presented with **328** mechanical vibrations in the pitch direction.
- The sessions will split into two parts, between which you will have 5 minutes break.

- As in the practice, after each motion you will be asked to rate the discomfort.
- Before each part, the experimenter will help you to adjust the seat belt.
- Please, wear the pair of headphones and close your eyes during the test.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

Please read carefully Part 3 of this sheet, where it is explained how to rate discomfort and body locations.

3. Rate the discomfort and body location:

- Your task is to say the discomfort caused by each of the **vibration stimuli** using any **positive** number that appears appropriate – whole numbers, decimals, or fractions.
- The first stimulus you will be presented with will be your reference in terms of discomfort. We suggest you start with a rating of 100. This stimulus will be repeated several times so that you become familiar with how it feels.
- Please judge the discomfort caused by the following stimuli relative to the discomfort caused by the first stimulus. For example;
    - if you feel the discomfort caused by the a stimulus is double the discomfort caused by the first stimulus, you should say ‘200’.
    - if you feel the discomfort caused by a stimulus is half the discomfort caused by the first stimulus, you should say ‘50’.
- Say ‘Repeat’ if you are unsure and wish to feel a motion again.

A.2 Experiment presented in Chapter 5

INSTRUCTIONS

This experiment is designed to understand your impression of discomfort caused by multi-axis whole-body vibration.

You will be presented with about 200 mechanical vibrations similar to those you may experience in a car.

Please read **carefully** and follow the instructions below.

---

4. **Preparation**
   - Sit comfortably in the seat.
     - The experimenter will help you to adjust your seat belt.
     - Keep the seat belt fastened and do not touch it during the experiment.
     - Wear the pair of headphones
     - Rest your hands on your lap.
     - Close your eyes.
     - Please maintain the same body posture throughout the experiment.
   - Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.
5. **Practice**
   - You will first be given a practice session to familiarise you with the motion stimuli and the procedure. Ask questions if you are unsure.
6. **Experiment**
   - The experiment has three parts, between which you will have 5 minutes break.
7. **Rating your discomfort:**
   - Your task is to rate the difference in discomfort between pairs of motions.
   - Use the following six-point category scale to choose your responses:
     - +3: First motion caused very much more discomfort than second motion.
     - +2: First motion caused much more discomfort than second motion.

    - +1: First motion caused slightly more discomfort than second motion.
    - -1: Second motion caused slightly more discomfort than first motion.
    - -2: Second motion caused much more discomfort than first motion.
    - -3: Second motion caused very much more discomfort than first motion.

- Say ‘Repeat’ if you are unsure and wish to feel a pair of motions again.

A.3 Experiment presented in Chapter 6

INSTRUCTIONS

This experiment is designed to understand your impression of discomfort caused by translational vibration with different magnitudes and directions.

You will be presented with a series of vibration stimuli.

Please read **carefully** and follow the instructions below.

Preparation:

8. **Practice**

- As a preliminary practice, you will be asked to judge lengths of lines on a piece of paper to make sure you understand the judgement.
- You will be given a brief practice session so as to familiarise you with the motion stimuli and the procedure before commencing the main experiment. Ask questions if you are unsure.
- During the practice please sit comfortably on the seat. Rest your hands on your lap.
- Wear the pair of headphones and close your eyes.
- **The experimenter will help you to adjust your seat belt. Please, keep your belt fastened and do not touch it during the experiment.**
- Please maintain the same body posture during the entire duration of the exposure.
- After each motion you will be asked to rate the discomfort. You will also be asked to locate the area of discomfort on the 'body amp' provided.
- The first motion experienced during the practice will be your "reference" for all the rest of the experiment.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

9. **Test**

- You will be presented with **240** mechanical vibrations in the three translational directions (fore-and-aft, lateral and vertical).
- The sessions will split into two parts, between which you will have 5 minutes break.
- As in the practice, after each motion you will be asked to rate the magnitude and location of the discomfort.

- Before each part, the experimenter will help you to adjust the seat belt.
- Please, wear the pair of headphones and close your eyes during the test.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

Please read carefully Part 3 of this sheet, where it is explained how to rate discomfort and body locations.

10. Rate the discomfort and body location:

- Your task is to say the discomfort caused by each of the **vibration stimuli** using any **positive** number that appears appropriate – whole numbers, decimals, or fractions.
- The first stimulus you will be presented with will be your reference in terms of discomfort. We suggest you start with a rating of 100. This stimulus will be repeated several times so that you become familiar with how it feels.
- Please judge the discomfort caused by the following stimuli relative to the discomfort caused by the first stimulus. For example;
    - if you feel the discomfort caused by a stimulus is double the discomfort caused by the first stimulus, you should say '200'.
    - if you feel the discomfort caused by a stimulus is half the discomfort caused by the first stimulus, you should say '50'.
- Say 'Repeat' if you are unsure and wish to feel a motion again.
- Locate the position of most discomfort and relate it to one of the locations on the 'body map' provided and give this location after the magnitude estimation.

A.4 Experiment presented in Chapter 7

INSTRUCTIONS

This experiment is designed to understand your impression of discomfort caused by translational vibration with different magnitudes and directions.

You will be presented with a series of vibration stimuli.

Please read **carefully** and follow the instructions below.

Preparation:

11. **Practice**

- As a preliminary practice, you will be asked to judge lengths of lines on a piece of paper to make sure you understand the judgement.
- You will be given a brief practice session so as to familiarise you with the motion stimuli and the procedure before commencing the main experiment. Ask questions if you are unsure.
- During the practice please sit comfortably on the seat. Rest your hands on your lap.
- Wear the pair of headphones and close your eyes.
- **The experimenter will help you to adjust your seat belt. Please, keep your belt fastened and do not touch it during the experiment.**
- Please maintain the same body posture during the entire duration of the exposure.
- After each motion you will be asked to rate the discomfort.
- The first motion experienced during the practice will be your "reference" for all the rest of the experiment.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

12. **Test**

- You will be presented with **233** mechanical vibrations in one, two or three of the three translational directions (fore-and-aft, lateral and vertical).
- The sessions will split into two parts, between which you will have 5 minutes break.
- As in the practice, after each motion you will be asked to rate the discomfort and the body location.

- Before each part, the experimenter will help you to adjust the seat belt.
- Please, wear the pair of headphones and close your eyes during the test.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

<u>Please read carefully Part 3 of this sheet, where it is explained how to rate discomfort and body locations.</u>

13. Rate the discomfort:

- Your task is to say the discomfort caused by each of the **vibration stimuli** using any **positive** number that appears appropriate – whole numbers, decimals, or fractions.
- The first stimulus you will be presented with will be your reference in terms of discomfort. We suggest you start with a rating of 100. This stimulus will be repeated several times so that you become familiar with how it feels.
- Please judge the discomfort caused by the following stimuli relative to the discomfort caused by the first stimulus. For example;
    - if you feel the discomfort caused by a stimulus is double the discomfort caused by the first stimulus, you should say ‘200’.
    - if you feel the discomfort caused by a stimulus is half the discomfort caused by the first stimulus, you should say ‘50’.
- Please also give a body location of most discomfort based on the body map provided.
- Say ‘Repeat’ if you are unsure and wish to feel a motion again.

Appendix B Comfort score equations from Chapter 5

B.1 Analysis of variance

Analysis of the subjective data from the experiment presented in Chapter 5 was carried out using Scheffe's method of paired comparison according to the description provided by Ebe (1998). For each part of the experiment the frequency that the judgements of the subjects fell into each category scale was calculated and summarised in Tables B1 and B2. The values of X_{ij} were calculated as in the following example:

Original – 50% x = ((9 x -1) + (6 x 1)) = -3

Table B1 Frequency of subjective judgements falling into each category for 36 pairs of vibration stimuli (part 1, 50% reduction)

	Category scale						X_{ij}	X_{ij}^2
	-3	-2	-1	1	2	3		
Original - 50% X	0	0	9	6	0	0	-3	9
50% X - Original	0	0	10	5	0	0	-5	25
Original - 50% Y	0	0	3	12	0	0	9	81
50% Y - Original	0	0	9	6	0	0	-3	9
Original - 50% Z	0	0	9	6	0	0	-3	9
50% Z - Original	0	0	10	5	0	0	-5	25
Original - 50% Roll	0	0	10	5	0	0	-5	25
50% Roll - Original	0	0	4	11	0	0	7	49
Original - 50% Pitch	0	0	10	5	0	0	-5	25
50% Pitch - Original	0	0	5	10	0	0	5	25
50% X - 50% Y	0	0	10	5	0	0	-5	25
50% Y - 50% X	0	0	13	2	0	0	-11	121
50% X - 50% Z	0	0	8	7	0	0	-1	1
50% Z - 50% X	0	0	7	8	0	0	1	1
50% X - 50% Roll	0	0	9	6	0	0	-3	9

50% Roll - 50% X	0	0	13	2	0	0	-11	121
50% X - 50% Pitch	0	0	9	6	0	0	-3	9
50% Pitch - 50% X	0	0	9	6	0	0	-3	9
50% Y - 50% Z	0	0	14	1	0	0	-13	169
50% Z - 50% Y	0	0	12	3	0	0	-9	81
50% Y - 50% Roll	0	0	12	3	0	0	-9	81
50% Roll - 50% Y	0	0	12	3	0	0	-9	81
50% Y - 50% Pitch	0	0	8	7	0	0	-1	1
50% Pitch - 50% Y	0	0	8	7	0	0	-1	1
50% Z - 50% roll	0	0	8	7	0	0	-1	1
50% Roll - 50% Z	0	0	10	5	0	0	-5	25
50% Z - 50% Pitch	0	0	12	3	0	0	-9	81
50% Pitch - 50% Z	0	0	11	4	0	0	-7	49
50% Roll - 50% Pitch	0	0	6	9	0	0	3	9
50% Pitch - 50% Roll	0	0	7	8	0	0	1	1
Sum	0	0	277	173	0	0	-104	10816

Table B2 Frequency of subjective judgements falling into each category for 36 pairs of vibration stimuli (part 1, 100% reduction)

	Category scale						X_{ij}	X_{ij}^2
	-3	-2	-1	1	2	3		
Original - 0% X	1	2	8	4	0	0	-11	121
0% X - Original	0	3	5	5	1	1	-1	1
Original - 0% Y	0	0	3	8	4	0	13	169
0% Y - Original	0	0	10	4	1	0	-4	16
Original - 0% Z	0	1	3	8	2	1	10	100
0% Z - Original	1	3	7	4	0	0	-12	144
Original - 0% Roll	0	2	5	6	2	0	1	1
0% Roll - Original	0	2	6	4	3	0	0	0

Original - 0% Pitch	0	2	8	4	1	0	-6	36
0% Pitch - Original	0	0	5	7	3	0	8	64
0% X - 0% Y	0	6	6	3	0	0	-15	225
0% Y - 0% X	0	2	7	6	0	0	-5	25
0% X - 0% Z	0	0	9	4	1	1	0	0
0% Z - 0% X	0	3	4	8	0	0	-2	4
0% X - 0% Roll	0	1	8	4	1	1	-1	1
0% Roll - 0% X	2	7	5	1	0	0	-24	576
0% X - 0% Pitch	0	2	9	4	0	0	-9	81
0% Pitch - 0% X	0	4	8	3	0	0	-13	169
0% Y - 0% Z	0	5	7	3	0	0	-14	196
0% Z - 0% Y	0	3	5	6	1	0	-3	9
0% Y - 0% Roll	2	6	4	3	0	0	-19	361
0% Roll - 0% Y	0	2	10	3	0	0	-11	121
0% Y - 0% Pitch	0	4	4	6	0	1	-3	9
0% Pitch - 0% Y	0	1	2	7	5	0	13	169
0% Z - 0% roll	0	1	5	8	1	0	3	9
0% Roll - 0% Z	1	7	5	1	1	0	-19	361
0% Z - 0% Pitch	0	5	7	3	0	0	-14	196
0% Pitch - 0% Z	2	0	9	3	1	0	-10	100
0% Roll - 0% Pitch	0	2	8	3	2	0	-5	25
0% Pitch - 0% Roll	0	2	9	4	0	0	-9	81
Sum	9	78	191	137	30	5	-162	26244

B.2 Variance of the primary effect (effect of six stimuli)

Tables B3 and B4 show the variance for the primary effect of the different motions. The sums of squares for the primary effect, S_α, and the degrees of freedom, F_α, were calculated as:

$S_\alpha = \Sigma(xi.. - x.j.)^2 / (2tp)$where t is the number of samples (=6) and p is the number of subjects (=15). For part 1:

$f_\alpha = t - 1$

$S_\alpha = 2328 / (2 \times 6 \times 15) = 12.93$

$f_\alpha = 6 - 1 = 5$

For part 2:

$f_\alpha = t - 1$

$S_\alpha = 4502 / (2 \times 6 \times 15) = 25.01$

$f_\alpha = 6 - 1 = 5$

B.3 Variance for combination effect

The variance for the combination effect for each part was calculated using results from Tables B3 and B4 and are shown in Tables B5 and B6. The combination effect and its degrees of freedom, S_y and F_y, respectively, were calculated for part 1 as:

$S_\gamma = (\Sigma_j\Sigma_{i<j} (x_{ij.} - x_{ji.})^2 / (2p)) - S_\alpha = (1200 / 30) - 12.93 = 27.07$

$f_\gamma = {}_tC_2 - (t\text{-}1) = 15 - (t - 1) = 15 - 5 = 10$

and calculated for part 2 as:

$S_\gamma = (\Sigma_j\Sigma_{i<j} (x_{ij.} - x_{ji.})^2 / (2p)) - S_\alpha = (2685 / 30) - 25.01 = 64.49$

$f_\gamma = {}_tC_2 - (t\text{-}1) = 15 - (t - 1) = 15 - 5 = 10$

B.4 Variance of order effect

The variance of the order effect for parts 1 and 2 were calculated using the results from Tables B5 and B6 respectively, as shown in Tables B7 and B8. The order effect and its degrees of freedom, S_δ and f_δ, respectively, were calculated for part 1 as:

$S_\delta = \Sigma_j\Sigma_{i<j} (X_{ij.} + X_{ji.})^2 / (2p) = 3348 / 30 = 111.60$

$f_\delta = {}_tC_2 = (6 \times 5) / (2 \times 1) = 15$

and calculated for part 2 as:

$S_\delta = \Sigma_j\Sigma_{i<j} (X_{ij.} + X_{ji.})^2 / (2p) = 4577 / 30 = 152.57$

$f_\delta = {}_tC_2 = (6 \times 5) / (2 \times 1) = 15$

Table B3 Calculation of primary effect of stimulus (1st stimulus in column, 2nd stimulus in row) Part 1 50% reduction

		X_{ij}						**$X_{i..}$**	**$X_{.j.}$**	**$X_{i..} - X_{.j.}$**	**$(X_{i..} - X_{.j.})^2$**
		1st stimulus									
		Original	50% *x*	50% *y*	50% *z*	50% roll	50% pitch				
2nd stimulus	Original		-4	-7	-8	8	5	-6	-9	3	9
	50% *x*	-4		-17	0	-17	-6	-44	-23	-21	441
	50% *y*	13	-7		-10	-14	-1	-19	-55	36	1296
	50% *z*	-5	-3	-17		-11	-11	-47	-28	-19	361
	50% roll	-7	-4	-11	-1		2	-21	-32	11	121
	50% pitch	-6	-5	-3	-9	2		-21	-11	-10	100
	Sum	**-9**	**-23**	**-55**	**-28**	**-32**	**-11**	**-158**	**-158**	**0**	**2328**

Table B4 Calculation of primary effect of stimulus (1st stimulus in column, 2nd stimulus in row) Part 2 100% reduction

		X_{ij}						$X_{i..}$	$X_{.j.}$	$X_{i..} - X_{.j.}$	$(X_{i..} - X_{.j.})^2$
		1st stimulus									
		Original	0% *x*	0% *y*	0% *z*	0% roll	0% pitch				
2nd stimulus	Original		-1	-4	-12	0	8	-9	7	-16	256
	0% *x*	-11		-5	-2	-24	-13	-55	-26	-29	841
	0% *y*	13	-15		-3	-11	13	-3	-45	42	1764
	0% *z*	10	0	-14		-19	-19	-42	-28	-14	196
	0% roll	1	-1	-19	3		-9	-25	-59	34	1156
	0% pitch	-6	-9	-3	-14	-5		-37	-20	-17	289
	Sum	**7**	**-26**	**-45**	**-28**	**-59**	**-20**	**-171**	**-171**	**0**	**4502**

Table B5 Calculation for combination effect of stimuli, part 1, 50% reduction

	$X_{ij.} - X_{ji.}$						$(X_{ij.} - X_{ji.})^2$					
	Original	50% *x*	50% *y*	50% *z*	50% roll	50% pitch	Original	50% *x*	50% *y*	50% *z*	50% roll	50% pitch
Original		0	-20	-3	15	11		0	400	9	225	121
50% *x*			-10	3	-13	-1			100	9	169	1
50% *y*				7	-3	2				49	9	4
50% *z*					-10	-2					100	4
50% roll						0						0
50% pitch												
Sum	**0**	**0**	**-30**	**7**	**-11**	**10**	**0**	**0**	**500**	**67**	**503**	**130**
							$\Sigma_j \Sigma_{i<j} (X_{ij.} - X_{ji.})^2$					**1200**

Table B6 Calculation for combination effect of stimuli, part 2, 100% reduction

	$X_{ij.} - X_{ji.}$						$(X_{ij.} - X_{ji.})^2$					
	Original	0% *x*	0% *y*	0% *z*	0% roll	0% pitch	Original	0% *x*	0% *y*	0% *z*	0% roll	0% pitch
Original		10	-17	-22	-1	14		100	289	484	1	196
0% *x*			10	-2	-23	-4			100	4	529	16
0% *y*				11	8	16				121	64	256
0% *z*					-22	-5					484	25
0% roll						-4						16
0% pitch												
Sum	**0**	**10**	**-7**	**-13**	**-38**	**17**	**0**	**100**	**389**	**609**	**1078**	**509**
							$\Sigma_j \Sigma_{i<j} (X_{ij.} – X_{ji.})^2$					**2685**

Table B7 Calculation of order effect of stimuli, part 1, 50% reduction

	$X_{ij.} + X_{ji.}$						$(X_{ij.} + X_{ji.})^2$					
	Original	50% *x*	50% *y*	50% *z*	50% roll	50% pitch	Original	50% *x*	50% *y*	50% *z*	50% roll	50% pitch
Original		-8	6	-13	1	-1		64	36	169	1	1
50% *x*			-24	-3	-21	-11			576	9	441	121
50% *y*				-27	-25	-4				729	625	16
50% *z*					-12	-20					144	400
50% roll						4						16
50% pitch												
Sum	**0**	**-8**	**-18**	**-43**	**-57**	**-32**	**0**	**64**	**612**	**907**	**1211**	**554**
							$\Sigma_j\Sigma_{i<j} (X_{ij.} + X_{ji.})^2$					**3348**

Table B8 Calculation of order effect of stimuli, part 2, 100% reduction

	$X_{ij.} + X_{ji.}$						$(X_{ij.} + X_{ji.})^2$					
	Original	0% *x*	0% *y*	0% *z*	0% roll	0% pitch	Original	0% *x*	0% *y*	0% *z*	0% roll	0% pitch
Original		-12	9	-2	1	2		144	81	4	1	4
0% *x*			-20	-2	-25	-22			400	4	625	484
0% *y*				-17	-30	10				289	900	100
0% *z*					-16	-33					256	1089
0% roll						-14						196
0% pitch												
Sum	**0**	**-12**	**-11**	**-21**	**-70**	**-57**	**0**	**144**	**481**	**297**	**1782**	**1873**
							$\Sigma_j\Sigma_{i<j}\ (X_{ij.} + X_{ji.})^2$					**4577**

B.5 Total sum of squares

The total sum of squares and the total degrees of freedom, S_T and f_T, respectively, are calculated for part 1 as:

$S_T = \Sigma_i\Sigma_j\Sigma l x_{ijl}^2$ = $((-3)^2 \times 5) + ((-2)^2 \times 71) + ((-1)^2 \times 201) + ((+1)^2 \times 147) + ((+2)^2 \times 23) + ((+3)^2 \times 3) = 796$

$f_T = 2p \times {}_tC_2 = 30 * 15 = 450$

and calculated for part 2 as:

$S_T = \Sigma_i\Sigma_j\Sigma l x_{ijl}^2$ = $((-3)^2 \times 9) + ((-2)^2 \times 78) + ((-1)^2 \times 191) + ((+1)^2 \times 137) + ((+2)^2 \times 30) + ((+3)^2 \times 5) = 886$

$f_T = 2p \times {}_tC_2 = 30 * 15 = 450$

B.5 Error

The sum square for error and its degrees of freedom, S_e and f_e, respectively, are calculated for part 1 as:

$S_e = S_t - \Sigma x_{ij}^2 / p = 796 - 24336 / 15 = 826.40$

$fe = 2(p-1) \times {}_tC_2 = (2 \times 14) \times (6 \times 5) / (2 \times 1) = 420$

and calculated for part 2 as:

$S_e = S_t - \Sigma x_{ij}^2 / p = 886 - 24336 / 15 = 863.60$

$fe = 2(p-1) \times {}_tC_2 = (2 \times 14) \times (6 \times 5) / (2 \times 1) = 420$

Appendix C Wilcoxon matched pairs from Chapter 7

C.1 Wilcoxon matched pairs results for *α* values of tri-axial vibration

	X2, Y2, Z2	X2, Y2, Z4	X2, Y2, Z8	X2, Y4, Z2	X2, Y4, Z4	X2, Y4, Z8	X2, Y8, Z2	X2, Y8, Z4	X2, Y8, Z8	X4, Y2, Z2	X4, Y2, Z4	X4, Y2, Z8	X4, Y4, Z2	X4, Y4, Z4
X2, Y2, Z2		0.691	0.397	0.015	0.008	0.124	0.246	0.01	0.009	0.132	0.758	0.352	0.009	0.004
X2, Y2, Z4			0.46	0.02	0.057	0.124	0.196	0.01	0.025	0.363	0.438	0.776	0.013	0.002
X2, Y2, Z8				0.068	0.518	0.532	0.586	0.039	0.059	0.198	0.469	0.629	0.109	0.113
X2, Y4, Z2					0.532	0.796	0.492	0.372	0.586	0.289	0.035	0.068	0.5	0.862
X2, Y4, Z4						0.836	0.408	0.193	0.287	0.408	0.017	0.301	0.201	0.737
X2, Y4, Z8							0.828	0.393	0.234	0.758	0.142	0.084	0.223	0.372
X2, Y8, Z2								0.281	0.363	0.653	0.179	0.332	0.356	0.379
X2, Y8, Z4									0.346	0.084	0.085	0.018	0.408	0.266
X2, Y8, Z8										0.148	0.065	0.113	0.981	0.795
X4, Y2, Z2											0.281	0.82	0.088	0.163
X4, Y2, Z4												0.679	0.031	0.01
X4, Y2, Z8													0.031	0.031
X4, Y4, Z2														0.469
X4, Y4, Z4														
X4, Y4, Z8														
X4, Y8, Z2														
X4, Y8, Z4														
X4, Y8, Z8														
X8, Y2, Z2														
X8, Y2, Z4														
X8, Y2, Z8														
X8, Y4, Z2														
X8, Y4, Z4														
X8, Y4, Z8														
X8, Y8, Z2														
X8, Y8, Z4														

	X4, Y4, Z8	X4, Y8, Z2	X4, Y8, Z4	X4, Y8, Z8	X8, Y2, Z2	X8, Y2, Z4	X8, Y2, Z8	X8, Y4, Z2	X8, Y4, Z4	X8, Y4, Z8	X8, Y8, Z2	X8, Y8, Z4	X8, Y8, Z8
X2, Y2, Z2	0.001	0.022	0.079	0.015	0.023	0.003	0.004	0.001	0.002	0.002	0.003	0.039	0.019
X2, Y2, Z4	0.015	0.019	0.07	0.003	0.052	0.019	0.003	0.001	0.004	0.004	0.003	0.102	0.044
X2, Y2, Z8	0.047	0.171	0.435	0.041	0.03	0.02	0.015	0.005	0.02	0.026	0.018	0.102	0.102
X2, Y4, Z2	0.356	0.636	0.811	0.164	0.623	0.381	0.396	0.01	0.006	0.01	0.011	0.679	0.687
X2, Y4, Z4	0.256	0.379	0.723	0.191	0.756	0.352	0.163	0.002	0.023	0.013	0.025	0.616	0.523
X2, Y4, Z8	0.1	0.554	0.862	0.079	0.326	0.148	0.199	0.005	0.005	0.002	0.013	0.5	0.381
X2, Y8, Z2	0.257	0.379	0.918	0.148	0.334	0.155	0.717	0.013	0.039	0.01	0.022	0.472	0.199
X2, Y8, Z4	0.836	0.47	0.234	0.877	0.532	0.955	0.57	0.14	0.281	0.221	0.408	0.616	0.868
X2, Y8, Z8	0.811	0.65	0.332	0.572	0.796	0.523	0.594	0.017	0.026	0.017	0.064	0.586	0.523
X4, Y2, Z2	0.124	0.112	0.795	0.078	0.041	0.025	0.023	0.005	0.039	0.022	0.02	0.133	0.163
X4, Y2, Z4	0.014	0.055	0.102	0.003	0.026	0.01	0.011	0.001	0.002	0.002	0.001	0.085	0.011
X4, Y2, Z8	0.01	0.088	0.266	0.009	0.02	0.011	0.004	0.002	0.008	0.002	0.002	0.085	0.093
X4, Y4, Z2	0.605	0.258	0.352	0.679	0.868	0.523	0.842	0.056	0.177	0.102	0.044	0.925	0.931
X4, Y4, Z4	0.609	1	0.334	0.393	0.981	0.653	0.776	0.03	0.121	0.062	0.071	0.687	0.845
X4, Y4, Z8		0.554	0.421	0.438	0.679	0.733	0.758	0.023	0.079	0.02	0.112	0.794	0.795
X4, Y8, Z2			0.691	0.363	0.955	0.363	0.532	0.022	0.109	0.034	0.084	0.586	0.887
X4, Y8, Z4				0.179	0.301	0.363	0.196	0.011	0.076	0.025	0.025	0.145	0.231
X4, Y8, Z8					0.875	0.91	0.834	0.046	0.281	0.084	0.134	0.828	0.962
X8, Y2, Z2						0.308	0.706	0.047	0.287	0.07	0.044	0.523	0.796
X8, Y2, Z4							0.82	0.101	0.569	0.156	0.1	0.795	0.776
X8, Y2, Z8								0.158	0.334	0.158	0.266	0.705	0.943
X8, Y4, Z2									0.182	0.722	0.82	0.028	0.017
X8, Y4, Z4										0.753	0.46	0.14	0.112
X8, Y4, Z8											0.51	0.113	0.041
X8, Y8, Z2												0.006	0.027
X8, Y8, Z4													0.776

C.2 Wilcoxon matched pairs results for α values of dual-axis vibration

	X2, Y2	X2, Y4	X2, Y8	X2, Z2	X2, Z4	X2, Z8	X4, Y2	X4, Y4	X4, Y8	X4, Z2	X4, Z4	X4, Z8	X8, Y2	X8, Y4
X2, Y2		0.14	0.609	0.272	0.221	0.293	0.906	0.356	0.906	0.438	0.394	0.733	0.096	0.002
X2, Y4			0.103	0.807	0.778	0.638	0.034	0.46	0.148	0.73	0.778	0.706	0.6	0.038
X2, Y8				0.211	0.125	0.056	0.679	0.039	0.744	0.381	0.177	0.438	0.064	0.001
X2, Z2					0.552	0.944	0.109	0.82	0.163	0.649	0.753	0.249	0.583	0.012
X2, Z4						0.799	0.148	0.698	0.136	0.679	0.844	0.294	0.65	0.046
X2, Z8							0.088	0.959	0.227	0.796	0.807	0.625	0.733	0.016
X4, Y2								0.01	0.36	0.093	0.099	0.438	0.026	0.001
X4, Y4									0.177	0.981	0.875	0.496	0.532	0.003
X4, Y8										0.218	0.407	0.758	0.113	0.007
X4, Z2											0.754	0.701	0.221	0.005
X4, Z4												0.754	0.308	0.019
X4, Z8													0.158	0.006
X8, Y2														0.016
X8, Y4														
X8, Y8														
X8, Z2														
X8, Z4														
X8, Z8														
Y2, Z2														
Y2, Z4														
Y2, Z8														
Y4, Z2														
Y4, Z4														
Y4, Z8														
Y8, Z2														
Y8, Z4														

	X8, Y8	X8, Z2	X8, Z4	X8, Z8	Y2, Z2	Y2, Z4	Y2, Z8	Y4, Z2	Y4, Z4	Y4, Z8	Y8, Z2	Y8, Z4	Y8, Z8
X2, Y2	0.695	0.079	0.084	0.156	0.91	0.112	0.959	0.096	0.047	0.256	0.173	0.301	0.586
X2, Y4	0.603	0.53	0.507	0.65	0.14	0.47	0.433	0.47	0.221	0.778	0.706	0.532	0.723
X2, Y8	0.356	0.053	0.063	0.102	0.619	0.056	0.496	0.088	0.01	0.06	0.061	0.084	0.287
X2, Z2	0.554	0.51	0.433	0.776	0.47	0.556	0.263	0.917	0.196	0.722	0.66	0.836	0.795
X2, Z4	0.679	0.73	0.73	0.589	0.478	0.683	0.279	0.814	0.345	0.701	0.691	0.586	0.879
X2, Z8	0.679	0.532	0.57	0.641	0.653	0.551	0.48	0.844	0.117	0.53	0.608	0.653	0.983
X4, Y2	0.127	0.044	0.039	0.025	0.193	0.015	0.278	0.061	0.002	0.015	0.044	0.053	0.231
X4, Y4	0.865	0.301	0.356	0.256	0.438	0.177	0.754	0.65	0.057	0.334	0.326	0.421	0.943
X4, Y8	0.156	0.059	0.049	0.107	0.356	0.055	0.538	0.118	0.017	0.084	0.071	0.058	0.257
X4, Z2	0.756	0.432	0.33	0.248	1	0.311	0.422	0.78	0.075	0.514	0.463	0.501	0.877
X4, Z4	0.642	0.463	0.57	0.6	0.65	0.306	0.48	0.695	0.068	0.552	0.507	0.518	0.897
X4, Z8	0.723	0.28	0.182	0.279	0.917	0.099	0.889	0.308	0.055	0.315	0.272	0.278	0.619
X8, Y2	0.215	0.79	0.969	0.972	0.109	0.925	0.022	0.73	0.414	0.875	0.552	0.955	0.272
X8, Y4	0.003	0.033	0.071	0.021	0.003	0.071	0.003	0.01	0.062	0.034	0.041	0.034	0.011
X8, Y8		0.301	0.301	0.191	0.756	0.21	0.679	0.532	0.163	0.233	0.309	0.289	0.796
X8, Z2			0.929	0.965	0.221	0.955	0.147	0.73	0.594	0.615	0.944	0.851	0.382
X8, Z4				0.929	0.064	0.82	0.134	0.638	0.47	0.638	0.9	0.865	0.427
X8, Z8					0.196	0.975	0.198	0.583	0.507	0.9	0.807	0.826	0.33
Y2, Z2						0.152	0.861	0.331	0.041	0.379	0.191	0.233	0.532
Y2, Z4							0.213	0.701	0.505	0.875	0.79	0.975	0.569
Y2, Z8								0.311	0.055	0.131	0.3	0.306	0.446
Y4, Z2									0.114	0.972	0.701	0.733	0.906
Y4, Z4										0.422	0.53	0.496	0.215
Y4, Z8											0.972	0.955	0.605
Y8, Z2												0.972	0.433
Y8, Z4													0.133

Appendix D Individual participant results

D.1 Experiment presented in Chapter 4 – Comfort contours in terms of unweighted r.m.s.

Values of the exponent *n* for pitch oscillation without a backrest											
Frequency (Hz)	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0
Subject 1	0.15	0.36	0.49	0.35	0.48	0.41	0.24	0.43	0.40	0.43	0.23
Subject 2	0.80	1.00	0.96	0.97	0.67	0.51	0.51	0.27	0.33	0.43	-0.51
Subject 3	0.78	0.71	0.89	0.67	0.47	0.43	0.70	0.20	0.61	0.43	0.27
Subject 4	0.75	1.03	0.54	0.72	0.58	0.63	0.51	0.51	0.29	0.40	0.45
Subject 5	0.86	1.05	0.88	0.54	0.55	0.59	0.55	0.53	0.63	0.69	0.37
Subject 6	1.67	0.94	0.74	1.05	0.69	1.13	0.63	0.25	0.50	0.64	0.51
Subject 7	1.67	1.69	1.68	0.84	1.34	1.37	0.72	1.11	0.71	0.55	0.61
Subject 8	1.05	0.93	1.16	1.01	1.27	1.25	0.99	0.64	0.84	0.99	0.54
Subject 9	0.58	0.64	0.51	0.31	0.26	0.46	0.53	0.36	0.59	0.43	0.31
Subject 10	1.71	1.63	0.62	0.81	0.70	0.95	0.62	0.79	1.06	0.89	0.62

Subject 11	0.86	1.28	1.13	0.77	0.58	0.43	0.51	0.36	0.47	0.24	0.43
Subject 12	1.31	0.92	0.46	0.42	0.22	0.37	0.78	0.37	0.36	0.34	0.22
Subject 13	1.34	1.32	1.41	1.69	0.98	0.95	0.69	0.56	0.60	0.35	0.23
Subject 14	1.11	1.07	0.68	0.62	0.66	0.41	0.56	0.55	0.33	0.48	0.11
Subject 15	1.03	0.93	1.39	0.94	0.65	0.53	0.78	0.50	0.77	1.02	0.12
Median	**1.03**	**1.00**	**0.88**	**0.77**	**0.65**	**0.53**	**0.62**	**0.50**	**0.59**	**0.43**	**0.31**

Values of the constant *k* for pitch oscillation without a backrest											
Frequency (Hz)	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0
Subject 1	112.6	145.1	184.0	153.7	132.9	127.6	131.6	116.3	134.6	114.2	119.7
Subject 2	167.9	228.7	181.7	154.9	127.4	120.3	105.5	122.9	109.0	105.1	110.4
Subject 3	471.4	323.8	260.3	210.6	191.4	148.4	142.9	129.9	75.0	87.7	108.8
Subject 4	560.5	451.6	309.7	361.3	234.5	237.2	231.6	207.6	209.2	166.0	178.8
Subject 5	526.5	592.1	387.5	214.8	180.0	225.6	208.2	219.3	185.8	148.7	262.3
Subject 6	801.5	446.8	418.1	408.9	293.3	217.4	198.8	248.5	185.8	166.2	206.4

Subject 7	610.5	516.4	432.0	247.2	177.9	181.7	94.7	123.0	111.5	103.3	180.1
Subject 8	341.3	218.8	280.3	255.0	244.0	161.0	145.1	163.5	139.8	143.8	198.8
Subject 9	292.8	234.7	170.4	171.1	134.4	147.5	130.8	130.4	91.6	128.6	142.0
Subject 10	661.5	732.8	263.2	298.6	178.0	177.2	162.8	182.9	126.3	146.4	243.3
Subject 11	248.5	312.1	324.8	177.3	193.3	163.2	196.6	209.3	165.6	195.6	175.6
Subject 12	391.5	184.2	155.7	118.1	118.9	138.4	98.1	127.7	112.5	110.9	135.5
Subject 13	725.5	398.4	211.8	325.4	217.9	176.5	193.5	172.7	196.3	256.8	262.3
Subject 14	270.2	220.6	142.5	135.0	125.0	109.8	96.2	117.4	122.0	103.6	156.7
Subject 15	589.5	418.5	571.4	334.1	275.8	211.6	167.4	194.6	155.6	108.1	351.5
Median	**471.4**	**323.8**	**263.2**	**214.8**	**180.0**	**163.2**	**145.1**	**163.5**	**134.6**	**128.6**	**178.8**

Values of the exponent *n* for pitch oscillation with a backrest											
Frequency (Hz)	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0
Subject 1	0.21	0.21	0.69	0.61	0.50	0.21	0.28	0.64	0.43	0.70	0.58
Subject 2	0.99	0.92	1.06	0.88	0.57	1.10	0.58	1.13	1.05	0.73	1.18
Subject 3	0.97	0.77	0.96	0.75	0.52	0.59	0.38	0.63	0.87	0.99	0.73
Subject 4	1.26	1.00	1.31	1.46	1.31	1.00	0.69	1.30	1.25	1.91	0.94
Subject 5	0.90	0.93	0.60	0.77	0.70	0.60	0.72	0.77	0.84	0.88	0.68
Subject 6	0.45	1.46	1.84	1.75	2.25	0.74	0.96	1.26	2.87	1.43	1.15
Subject 7	0.90	1.66	1.63	1.09	0.28	0.60	0.78	1.69	1.95	1.72	0.92
Subject 8	0.88	1.19	1.50	1.15	0.95	0.85	0.85	1.13	1.50	1.53	1.23
Subject 9	0.47	0.40	0.50	0.70	0.13	0.33	0.62	0.98	0.81	0.63	0.45
Subject 10	2.43	0.84	1.20	1.19	0.99	1.36	1.74	1.18	0.51	1.51	1.52
Subject 11	0.89	0.89	1.19	1.22	0.82	0.68	0.99	0.67	0.77	1.08	0.52
Subject 12	1.62	1.45	1.35	0.09	0.78	0.74	0.59	-0.19	0.61	1.17	0.34
Subject 13	2.02	1.08	0.64	0.76	0.60	1.19	1.36	1.26	1.21	1.39	0.89

Subject 14	0.90	1.11	1.07	0.89	0.74	0.79	0.81	1.12	0.87	0.89	0.54
Subject 15	1.03	0.85	0.52	1.27	1.45	1.78	1.32	1.20	2.17	1.35	1.38
Median	**0.90**	**0.93**	**1.07**	**0.89**	**0.74**	**0.74**	**0.78**	**1.13**	**0.87**	**1.17**	**0.89**

Values of the constant *k* for pitch oscillation with a backrest											
Frequency (Hz)	0.5	0.63	0.8	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0
Subject 1	134.0	87.7	184.5	198.7	180.5	168.6	166.1	216.9	149.5	292.6	281.5
Subject 2	213.2	193.0	286.4	230.3	168.0	306.2	201.7	337.2	367.6	250.4	365.2
Subject 3	402.5	289.9	370.2	215.9	138.7	173.2	118.3	88.3	155.7	167.7	155.1
Subject 4	682.7	541.0	583.7	683.0	441.5	297.7	165.4	297.3	232.6	842.3	393.5
Subject 5	513.5	673.0	253.6	347.6	330.2	317.9	396.3	388.9	358.0	428.3	297.3
Subject 6	64.2	303.6	708.6	760.2	1016.9	275.5	281.9	484.3	2015.2	715.2	322.6
Subject 7	165.5	241.6	487.5	315.7	226.4	225.8	112.7	194.2	268.4	484.0	406.1
Subject 8	262.5	434.3	608.1	360.9	218.3	183.7	236.9	257.3	686.3	894.4	974.0
Subject 9	269.0	190.2	226.7	276.6	143.2	176.0	180.1	260.7	239.3	196.6	187.7

Subject 10	1800.3	195.7	315.2	380.2	245.4	582.2	1151.5	476.8	151.6	481.1	554.3
Subject 11	245.9	249.1	475.0	409.4	304.8	262.5	415.6	260.4	329.8	585.8	322.9
Subject 12	500.5	200.5	326.9	114.7	47.8	167.1	84.1	59.6	146.9	349.8	155.6
Subject 13	895.5	249.2	106.0	162.3	99.5	427.8	373.3	386.7	455.2	783.6	413.9
Subject 14	165.5	349.2	299.5	300.2	265.6	225.9	255.9	339.2	256.7	301.3	239.2
Subject 15	419.5	255.2	87.7	326.6	380.6	877.6	440.4	312.1	1987.0	1011.5	424.8
Median	**269.0**	**249.2**	**315.2**	**315.7**	**226.4**	**262.5**	**236.9**	**297.3**	**268.4**	**481.1**	**322.9**

D.2 Experiment presented in Chapter 5 – matched pairs results for each pair

Responses from 50% reduction paired comparisons test										
Stimulus pair	Original – 50%*x*	50% *x* – Original	Original – 50%*y*	50% *y* – Original	Original – 50%*z*	50% *z* – Original	Original – 50%roll	50% roll – Original	Original – 50%pitch	50% pitch – Original
Subject 1	-1	1	-1	1	-2	1	-1	-1	-2	-1
Subject 2	1	-1	-1	1	-1	-2	1	1	-1	1
Subject 3	-1	2	2	1	2	-2	-2	2	2	2
Subject 4	1	-1	1	1	1	1	-1	1	1	1
Subject 5	1	-1	2	1	1	-1	1	1	-2	-1
Subject 6	-1	1	1	-1	-1	1	-1	-1	-1	-1
Subject 7	-2	-1	1	-1	-2	-1	-1	-2	-2	1
Subject 8	-1	-1	2	-2	-1	1	-2	3	2	1
Subject 9	1	-1	1	-1	-2	-1	1	1	-1	1
Subject 10	1	-1	-1	-1	1	-2	1	1	-1	1

Subject 11	-1	1	1	-1	-1	-1	-1	1	-1	-1
Subject 12	-2	-1	1	-3	1	-1	1	1	1	1
Subject 13	-1	1	1	-1	-1	-1	-1	1	1	1
Subject 14	2	-1	2	-2	1	1	-1	-2	-1	-2
Subject 15	-1	-1	1	1	-1	-1	-1	1	-1	1

Responses from 50% reduction paired comparisons test										
Stimulus pair	50%x – 50% y	50% *y* – 50% *x*	50% *x* – 50% *z*	50% *z* – 50% *x*	50% *x* – 50% roll	50% roll – 50% *x*	50% *x* – 50% pitch	50% pitch – 50% *x*	50% *y* – 50% *z*	50% *z* – 50% *y*
Subject 1	-1	-2	1	-1	-1	-2	1	1	-1	-1
Subject 2	1	-1	-1	-1	1	-1	-1	-1	1	-1
Subject 3	3	-2	-2	1	-1	-2	2	-3	-1	-1
Subject 4	-1	-1	-1	-2	-1	-2	-2	-1	-2	1
Subject 5	-1	-1	-1	1	-1	-1	1	1	-1	-1
Subject 6	-1	-1	-1	1	-1	-1	-1	-1	-1	-1

Subject 7	-2	-2	1	1	1	1	-1	-1	-2	-1
Subject 8	-3	-2	2	2	1	-3	1	-2	-1	-2
Subject 9	-1	-2	1	-1	-2	1	1	1	-1	-1
Subject 10	-2	1	1	-1	-1	-1	-2	1	-1	-1
Subject 11	-1	-1	1	1	-1	-1	-1	-1	-2	1
Subject 12	1	1	-2	-2	1	-1	1	1	-1	1
Subject 13	-1	-1	-1	1	1	-1	-2	1	-1	-1
Subject 14	1	-2	-2	1	1	-2	-1	-1	-2	-1
Subject 15	1	-1	1	-1	-1	-1	-1	-1	-1	-1

Responses from 50% reduction paired comparisons test										
Stimulus pair	50% y – 50% roll	50% roll – 50% y	50% *y* – 50% pitch	50% pitch – 50% *y*	50% *z* – 50% roll	50% roll – 50% *z*	50% *z* – 50% pitch	50% pitch – 50% *z*	50% roll – 50% pitch	50% pitch – 50% roll
Subject 1	-1	-2	-1	-2	-1	-2	1	-1	-1	-1
Subject 2	-1	-1	1	-2	-1	1	-1	-2	1	-2
Subject 3	-1	-1	2	3	-2	-3	-1	-1	1	2
Subject 4	-1	-1	-2	-1	1	-2	-2	-1	-1	1
Subject 5	-1	-2	1	1	-1	-2	-1	-1	1	1
Subject 6	1	1	1	-1	1	1	-1	-1	1	1
Subject 7	1	1	1	1	1	-2	2	2	1	1
Subject 8	-1	-2	-1	2	-1	2	2	-1	-2	2
Subject 9	-1	-2	-2	-1	1	-1	-2	-2	1	-1
Subject 10	-1	1	-1	-2	1	-1	-1	1	-1	-1
Subject 11	-1	-1	-1	1	-1	-1	-1	-1	-1	-1
Subject 12	-2	-1	-1	-1	-1	1	-1	-2	-1	1

Subject 13	-2	-1	1	1	-1	1	-1	-1	1	-1
Subject 14	-1	-2	-2	1	2	-2	-1	1	1	1
Subject 15	1	-1	1	-1	1	-1	-1	1	1	-1

Responses from 100% reduction paired comparisons test										
Stimulus pair	Original – 0%*x*	0% *x* – Original	Original – 0%*y*	0% *y* – Original	Original – 50%*z*	0% *z* – Original	Original – 0%roll	0% roll – Original	Original – 0%pitch	0% pitch – Original
Subject 1	-1	1	1	-1	2	-1	-1	-1	-1	-1
Subject 2	-1	-2	2	2	1	-1	-2	2	-1	1
Subject 3	-1	3	2	-1	1	-2	2	2	-1	2
Subject 4	-1	-1	1	-1	-1	-1	-2	-1	1	1
Subject 5	1	1	1	-1	-1	-1	2	1	-2	1
Subject 6	1	-1	-1	1	1	1	1	-1	-1	-1
Subject 7	-2	-1	1	-1	-2	1	1	-2	1	-1
Subject 8	-3	2	2	-1	2	-3	1	-2	-2	2

Subject 9	-1	-2	2	-1	1	-2	-1	-1	1	-1
Subject 10	-1	1	-1	-1	1	-1	-1	1	-1	1
Subject 11	1	1	-1	-1	1	-1	-1	1	-1	1
Subject 12	1	-1	1	1	1	-2	1	-1	1	1
Subject 13	-1	-1	1	1	-1	-1	1	-1	-1	-1
Subject 14	-2	-2	1	-1	3	1	-1	2	2	2
Subject 15	-1	1	1	1	1	1	1	1	-1	1

Responses from 100% reduction paired comparisons test										
Stimulus pair	0%x – 0% y	0% *y* – 0% *x*	0% *x* – 0% *z*	0% *z* – 0% *x*	0% *x* – 0% roll	0% roll – 0% *x*	0% *x* – 0% pitch	0% pitch – 0% *x*	0% *y* – 0% *z*	0% *z* – 0% *y*
Subject 1	-1	1	-1	-2	-1	-2	1	-2	-1	1
Subject 2	1	-1	-1	1	1	-2	-2	-1	-2	-1
Subject 3	-2	-1	3	1	3	-3	-1	-2	-2	-2
Subject 4	-1	-2	1	-1	1	-1	-2	-1	-2	-1

Subject 5	-2	-1	-1	1	-1	-2	-1	-1	-2	1
Subject 6	1	-1	-1	1	-1	-1	-1	1	-1	-1
Subject 7	-2	1	-1	-1	1	1	1	-1	-1	2
Subject 8	-2	-2	-1	-2	2	-2	-1	-2	-1	-1
Subject 9	-1	1	1	-2	-1	-3	1	1	1	-2
Subject 10	-2	-1	1	1	1	-2	-1	1	-1	1
Subject 11	-1	1	-1	-1	-1	-1	1	-1	1	1
Subject 12	-1	1	-1	1	-1	-1	-1	-1	-1	-1
Subject 13	-2	-1	-1	1	-1	-2	-1	-1	1	1
Subject 14	1	1	2	-1	-2	-2	-1	-2	-2	-2
Subject 15	-1	-1	1	1	-1	-1	-1	-1	-1	1

Responses from 100% reduction paired comparisons test										
Stimulus pair	0% y – 0% roll	0% roll – 0% y	0% *y* – 0% pitch	0% pitch – 0% *y*	0% *z* – 0% roll	0% roll – 0% *z*	0% *z* – 0% pitch	0% pitch – 0% *z*	0% roll – 0% pitch	0% pitch – 0% roll
Subject 1	-2	1	1	1	-1	-2	-1	1	-1	-2
Subject 2	-3	1	-1	1	-1	-2	-1	-3	2	1
Subject 3	-3	-2	1	2	2	-3	1	-3	1	-1
Subject 4	-2	-1	-2	-1	1	-2	-2	-1	-1	1
Subject 5	-2	-1	-2	2	1	-1	-2	-1	-2	-1
Subject 6	1	-1	1	1	-1	-1	1	-1	1	-1
Subject 7	-2	-1	1	1	1	1	-1	1	-1	-1
Subject 8	-1	1	3	-2	-2	2	-2	2	1	-1
Subject 9	-2	-1	-2	2	1	-2	-2	-1	2	-2
Subject 10	-1	-1	-1	-1	-1	-1	-1	-1	-2	1
Subject 11	-1	-1	-1	1	1	-2	-1	-1	-1	-1
Subject 12	1	-1	1	2	1	-2	-2	-1	-1	-1

Subject 13	-2	-1	1	1	1	-2	-1	-1	-1	-1
Subject 14	1	-2	-2	2	-1	-1	1	-1	-1	1
Subject 15	-1	-1	-1	1	1	-1	-1	1	-1	-1

D.3 Experiment presented in Chapter 6 – Comfort contours in terms of unweighted r.m.s.

Values of the exponent *n* for fore-and-aft vibration without a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	1.19	1.39	0.88	1.04	1.06	0.41	0.38	0.29	0.56	0.55	1.11
Subject 2	0.26	1.25	0.70	1.49	1.02	0.59	1.06	1.00	0.52	1.16	0.54
Subject 3	0.85	1.17	1.00	1.09	0.62	0.51	0.39	0.53	0.67	1.25	0.57
Subject 4	0.83	0.07	1.48	1.20	1.61	1.49	1.36	1.23	0.47	-0.14	0.26
Subject 5	0.33	0.41	0.45	0.45	0.36	0.32	0.22	0.23	0.24	0.29	0.35
Subject 6	1.08	0.75	0.56	1.32	0.88	1.09	0.99	0.53	0.70	0.51	1.10
Subject 7	0.68	1.16	0.86	0.88	0.88	0.77	0.73	0.46	0.45	0.42	0.62
Subject 8	1.19	1.05	1.06	1.32	1.34	0.21	0.46	0.35	0.42	0.21	0.96
Subject 9	0.52	0.43	0.57	0.45	0.49	0.52	0.36	0.34	0.40	0.43	0.43
Subject 10	0.36	0.30	0.25	0.76	0.51	0.27	0.36	0.18	0.27	0.36	0.32
Subject 11	0.44	0.38	0.17	0.52	0.30	0.31	0.49	0.42	0.31	0.23	0.50
Subject 12	1.08	1.38	0.89	0.75	1.13	1.69	0.36	1.24	0.94	1.29	1.29
Subject 13	0.91	0.65	0.73	0.64	0.76	0.69	0.38	0.27	0.22	0.27	0.37
Subject 14	0.42	0.40	0.35	0.35	0.49	0.25	0.27	0.11	0.19	0.27	0.29

Subject 15	0.10	0.36	0.65	0.49	0.28	0.52	0.30	0.34	0.31	0.29	0.26
Subject 16	0.31	0.34	0.29	0.25	0.33	0.44	0.33	0.16	0.22	0.30	0.31
Subject 17	0.23	0.11	0.23	0.22	0.15	0.19	0.13	0.12	0.14	0.11	0.14
Subject 18	1.04	0.99	1.38	1.35	1.51	0.84	0.92	0.83	0.97	0.73	0.48
Subject 19	0.36	0.14	0.28	0.25	0.11	0.34	0.20	0.07	0.06	0.15	0.20
Subject 20	0.14	0.15	0.12	0.12	0.27	0.21	0.14	0.13	0.12	0.16	0.18
Subject 21	1.76	1.48	1.50	1.36	1.14	0.51	0.25	0.28	0.48	0.30	0.31
Subject 22	0.23	0.26	0.41	0.48	0.44	0.32	0.20	0.23	0.22	0.21	0.27
Subject 23	0.56	0.35	0.55	0.60	0.75	0.66	0.20	0.53	0.63	0.30	0.30
Subject 24	0.81	0.43	0.57	0.43	0.79	0.75	0.57	0.50	0.45	0.32	0.49
Median	**0.54**	**0.42**	**0.57**	**0.62**	**0.68**	**0.51**	**0.36**	**0.34**	**0.41**	**0.30**	**0.36**

Values of the constant *k* for fore-and-aft vibration without a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	284.5	238.6	166.0	240.7	299.2	234.5	232.4	183.2	131.1	98.8	55.7
Subject 2	202.4	375.8	249.9	670.0	415.9	267.7	152.5	144.1	131.6	40.4	70.3
Subject 3	164.7	335.6	276.8	367.1	197.6	153.0	127.2	92.2	109.0	78.4	111.1

Subject 4	212.6	45.8	517.6	346.8	431.1	568.4	546.8	394.2	300.2	305.6	274.6
Subject 5	164.1	136.3	139.8	169.2	175.6	143.1	118.3	114.5	114.2	116.3	101.7
Subject 6	365.3	227.5	160.4	540.8	323.9	333.3	301.1	188.0	143.5	146.8	94.8
Subject 7	224.5	408.8	232.5	287.4	325.3	308.6	234.6	180.2	185.2	129.9	106.1
Subject 8	365.3	321.2	259.3	321.3	348.5	130.5	162.1	106.2	102.9	122.6	78.4
Subject 9	159.8	175.2	197.0	161.2	164.0	167.8	147.9	136.4	110.0	108.9	97.1
Subject 10	150.3	125.4	118.2	185.1	150.6	132.9	125.2	123.6	110.1	97.3	90.5
Subject 11	175.5	165.6	134.8	169.8	145.2	126.7	123.5	111.5	98.5	94.6	74.8
Subject 12	431.1	553.4	210.5	220.2	270.9	460.7	350.4	353.6	205.1	162.9	119.1
Subject 13	219.9	159.7	155.5	154.0	162.8	179.3	129.1	114.4	109.3	98.4	101.9
Subject 14	156.6	153.4	132.7	148.8	180.2	149.6	151.5	132.1	125.0	109.8	100.7
Subject 15	125.3	159.4	212.5	166.9	183.9	189.7	151.2	143.1	104.5	104.7	92.8
Subject 16	128.3	138.5	132.7	123.2	139.1	158.6	144.1	129.7	123.0	112.2	112.5
Subject 17	136.7	108.2	138.2	141.1	124.5	117.2	110.9	101.8	104.2	104.6	103.6
Subject 18	203.6	188.9	375.9	412.0	545.6	270.1	239.1	159.2	187.9	161.9	174.4
Subject 19	169.5	124.1	126.3	111.6	107.8	123.9	109.4	91.9	94.9	88.5	89.0
Subject 20	121.9	116.4	115.2	117.3	137.7	129.2	126.1	117.6	108.4	98.1	100.4

Subject 21	324.0	293.7	271.0	267.4	260.4	176.0	141.7	138.5	131.8	134.6	109.6
Subject 22	122.1	118.7	140.8	156.0	164.0	141.9	125.9	107.9	104.0	99.3	98.5
Subject 23	212.1	159.2	191.3	213.5	228.6	197.4	148.1	107.6	94.1	106.0	105.1
Subject 24	209.0	146.0	152.3	129.6	163.7	191.2	176.4	152.1	145.4	114.3	114.1
Median	**188.9**	**159.5**	**163.2**	**177.5**	**182.1**	**171.9**	**148.0**	**130.9**	**112.1**	**107.5**	**101.2**

Values of the exponent *n* for lateral vibration without a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	1.45	1.54	1.24	0.92	0.70	0.97	0.93	0.83	0.98	0.96	1.37
Subject 2	1.12	1.15	1.11	0.80	0.73	1.51	1.09	0.85	0.96	0.60	0.67
Subject 3	1.18	0.97	1.50	0.65	0.47	0.67	0.33	0.58	0.73	0.39	0.62
Subject 4	0.18	1.45	1.64	1.19	0.49	0.95	1.14	0.26	0.73	1.02	0.41
Subject 5	0.41	0.35	0.70	0.48	0.30	0.34	0.31	0.34	0.23	0.27	0.36
Subject 6	0.88	0.97	1.38	0.94	0.86	1.02	0.79	0.64	0.39	0.21	0.09
Subject 7	0.61	0.81	1.11	0.84	0.69	0.87	0.80	0.70	0.47	0.48	0.56
Subject 8	1.60	0.91	1.20	1.47	0.84	0.66	0.42	0.42	0.76	0.68	0.43
Subject 9	0.43	0.48	0.44	0.49	0.30	0.42	0.26	0.30	0.25	0.20	0.33

Subject 10	0.34	0.77	0.51	0.60	0.40	0.34	0.34	0.36	0.21	0.09	0.15
Subject 11	0.15	0.39	0.43	0.45	0.33	0.27	0.49	0.41	0.37	0.29	0.32
Subject 12	1.61	1.03	1.45	1.63	1.47	1.03	0.30	1.02	1.04	0.95	0.88
Subject 13	0.64	0.70	0.61	0.58	0.68	0.21	0.40	0.38	0.27	0.27	0.26
Subject 14	0.22	0.40	0.51	0.31	0.30	0.21	0.10	0.22	0.30	0.19	0.22
Subject 15	0.45	0.57	0.57	0.53	0.43	0.13	0.26	0.38	0.16	0.41	0.45
Subject 16	0.31	0.26	0.40	0.42	0.35	0.29	0.39	0.33	0.17	0.26	0.27
Subject 17	0.25	0.15	0.09	0.18	0.20	0.18	0.17	0.21	0.12	0.13	0.17
Subject 18	0.70	1.09	0.82	1.39	0.78	0.69	0.84	1.01	0.81	0.66	0.72
Subject 19	0.41	0.31	0.31	0.71	0.09	0.19	0.21	0.24	0.20	0.18	0.16
Subject 20	0.20	0.23	0.27	0.18	0.11	0.16	0.14	0.17	0.09	0.10	0.16
Subject 21	1.61	1.87	2.05	1.72	0.96	0.28	0.63	0.41	0.32	0.22	0.29
Subject 22	0.34	0.31	0.25	0.25	0.27	0.32	0.06	0.22	0.18	0.28	0.19
Subject 23	0.72	0.57	0.83	0.43	0.57	0.68	0.44	0.53	0.05	0.59	0.31
Subject 24	0.74	0.45	0.86	0.60	0.57	0.41	0.56	0.20	0.72	0.54	0.32
Median	**0.53**	**0.63**	**0.76**	**0.60**	**0.48**	**0.37**	**0.39**	**0.38**	**0.31**	**0.28**	**0.32**

Values of the constant *k* for lateral vibration without a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	351.3	424.0	303.6	357.7	295.6	266.2	204.2	136.2	114.2	100.6	60.6
Subject 2	282.0	376.5	426.7	262.1	211.1	219.4	187.6	111.6	61.4	25.9	33.8
Subject 3	246.1	213.6	404.7	180.0	179.4	180.5	109.9	143.7	145.5	127.4	122.2
Subject 4	97.8	373.5	636.9	536.7	340.6	285.4	251.5	129.9	125.3	152.9	277.3
Subject 5	162.8	136.6	249.9	170.0	144.2	128.4	128.3	120.2	104.4	109.3	114.2
Subject 6	234.7	183.1	467.6	332.2	302.3	256.5	214.6	178.0	143.7	134.3	158.8
Subject 7	224.2	290.9	370.9	325.9	305.8	264.0	224.8	190.9	166.9	132.9	120.9
Subject 8	526.3	228.2	399.6	505.0	207.3	209.2	157.8	116.4	127.2	116.2	137.0
Subject 9	138.4	167.3	180.9	194.0	123.0	140.9	117.7	118.1	122.5	121.0	107.6
Subject 10	132.8	190.5	168.6	196.5	143.8	120.9	111.9	115.5	104.0	104.4	105.2
Subject 11	132.3	147.0	152.4	187.2	135.9	107.6	109.6	102.3	112.5	94.1	101.9
Subject 12	627.4	188.0	633.7	684.2	560.7	366.0	238.0	251.2	190.1	141.7	127.0
Subject 13	158.4	133.3	165.2	165.8	161.2	108.6	121.8	113.6	110.1	102.9	114.1
Subject 14	104.7	142.7	170.4	161.0	161.9	135.6	121.1	112.0	118.3	112.5	108.6
Subject 15	175.7	177.7	179.1	188.2	185.2	139.8	143.2	103.0	130.1	110.0	82.6

Subject 16	132.9	126.2	165.5	174.1	155.6	135.8	142.9	133.5	113.9	119.2	116.7
Subject 17	141.4	127.3	123.5	122.6	121.5	114.6	114.1	114.1	109.2	101.3	103.8
Subject 18	166.9	352.9	311.3	721.6	265.0	271.4	150.7	135.9	148.4	191.5	153.9
Subject 19	158.8	134.6	135.1	193.0	108.1	106.2	108.0	102.5	100.4	91.0	92.5
Subject 20	125.7	120.9	150.3	123.5	123.0	122.7	118.6	105.1	112.1	107.2	102.3
Subject 21	319.5	394.7	445.0	429.7	224.7	128.4	150.3	124.9	111.7	102.6	102.1
Subject 22	140.9	135.8	135.0	138.9	133.7	124.6	101.2	104.6	113.9	98.4	112.7
Subject 23	267.5	212.5	264.5	207.3	198.3	190.2	132.4	138.5	104.1	97.4	106.4
Subject 24	170.1	103.3	232.2	192.3	173.5	145.5	141.5	110.1	106.4	110.3	134.4
Median	**164.9**	**180.4**	**241.1**	**193.5**	**176.5**	**140.3**	**137.0**	**117.3**	**113.9**	**109.7**	**110.7**

Values of the exponent *n* for vertical vibration without a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	1.07	1.76	2.01	1.32	1.97	1.65	1.60	1.13	1.10	1.67	1.02
Subject 2	1.55	1.80	1.83	0.98	1.62	1.81	0.90	1.11	1.23	1.21	1.57
Subject 3	1.26	1.33	1.17	0.96	0.81	0.61	1.11	0.79	0.73	0.72	0.61
Subject 4	1.16	1.33	1.24	0.37	0.48	1.05	1.28	0.97	1.06	1.07	0.14
Subject 5	0.60	0.76	0.69	0.73	0.56	0.44	0.65	0.36	0.48	0.42	0.57
Subject 6	1.38	1.45	0.86	1.91	0.97	1.38	1.48	1.44	1.22	1.09	1.35
Subject 7	0.87	0.90	0.87	0.61	1.19	1.14	1.62	0.87	0.63	0.74	0.72
Subject 8	1.70	1.55	1.30	1.38	1.10	1.08	1.50	0.98	1.14	1.38	0.95
Subject 9	0.64	0.60	0.48	0.49	0.55	0.21	0.47	0.34	0.29	0.34	0.54
Subject 10	0.40	0.61	0.48	0.30	0.55	0.61	0.35	0.54	0.42	0.61	0.57
Subject 11	0.46	0.58	0.69	0.64	0.73	0.92	0.52	0.61	0.37	0.72	0.47
Subject 12	0.16	1.70	1.15	1.52	0.96	0.52	0.56	1.02	1.22	1.35	1.41
Subject 13	0.99	0.66	0.46	0.73	0.58	0.82	0.87	0.48	0.25	0.84	0.70
Subject 14	0.59	0.27	0.40	0.49	0.33	0.35	0.21	0.42	0.31	0.42	0.20
Subject 15	0.97	0.94	0.39	0.57	0.80	0.50	0.76	0.51	0.40	0.51	0.27

Subject 16	0.56	0.50	0.46	0.45	0.31	0.42	0.24	0.32	0.41	0.29	0.28
Subject 17	0.35	0.29	0.24	0.23	0.19	0.19	0.20	0.03	0.04	0.14	0.20
Subject 18	0.98	1.20	1.04	1.57	1.59	1.58	1.11	1.59	1.06	0.78	0.79
Subject 19	1.04	0.74	0.37	0.39	0.75	0.95	0.55	0.36	0.14	0.35	0.81
Subject 20	0.25	0.28	0.29	0.24	0.11	0.25	0.25	0.20	0.10	0.20	0.20
Subject 21	1.75	1.60	1.82	1.76	1.53	1.45	0.87	1.41	0.13	0.53	1.25
Subject 22	0.54	0.31	0.35	0.31	0.42	0.32	0.43	0.37	0.20	0.31	0.26
Subject 23	0.88	0.43	0.58	0.90	0.51	0.62	0.64	0.77	0.58	0.78	0.29
Subject 24	0.57	0.61	0.78	0.90	0.63	0.82	0.99	0.78	0.63	0.62	0.83
Median	**0.87**	**0.75**	**0.69**	**0.69**	**0.68**	**0.72**	**0.70**	**0.69**	**0.45**	**0.67**	**0.59**

Values of the constant *k* for vertical vibration without a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	71.1	75.2	92.0	114.9	169.0	264.5	521.1	364.8	232.1	440.8	155.4
Subject 2	154.8	119.1	160.9	183.8	282.1	458.8	175.9	283.5	358.8	274.5	419.4
Subject 3	73.7	76.5	77.1	77.1	106.3	128.5	313.6	208.5	227.0	276.6	212.5
Subject 4	74.9	83.9	52.0	68.8	49.9	118.8	273.3	138.9	596.1	328.0	314.8

Subject 5	129.9	117.6	119.6	130.2	111.6	109.9	152.0	138.5	169.9	160.6	193.8
Subject 6	86.0	94.1	67.4	125.3	126.4	180.7	320.0	338.8	357.7	242.7	358.1
Subject 7	125.8	147.0	122.4	133.9	167.6	210.3	401.3	317.2	234.0	236.8	220.1
Subject 8	81.6	76.4	84.9	107.1	131.0	145.8	376.2	303.0	305.3	334.7	248.0
Subject 9	105.7	110.2	101.0	98.0	114.1	100.3	145.0	155.3	140.3	136.8	178.9
Subject 10	108.6	108.4	98.8	102.2	109.6	118.0	106.0	139.4	140.3	153.8	133.1
Subject 11	139.1	131.9	132.5	124.8	142.4	188.2	182.9	215.3	161.5	214.3	182.6
Subject 12	46.5	122.3	127.2	172.8	122.5	128.9	497.8	410.1	502.4	755.8	661.0
Subject 13	108.4	88.0	100.1	100.6	107.8	131.9	216.6	157.5	113.9	214.7	168.3
Subject 14	87.4	92.1	94.7	111.7	114.8	113.6	112.3	150.8	164.6	176.9	126.9
Subject 15	108.9	123.6	118.0	129.0	140.4	153.4	198.1	182.2	138.7	159.8	116.3
Subject 16	119.7	124.8	119.6	100.3	115.2	125.4	105.4	120.4	150.3	126.4	138.0
Subject 17	114.2	115.4	107.2	107.3	106.4	115.8	122.2	101.4	97.8	111.2	129.0
Subject 18	122.3	126.9	124.5	161.0	197.1	213.2	229.6	524.6	441.5	472.0	280.1
Subject 19	113.8	100.4	107.2	81.1	107.7	160.9	114.6	136.1	104.1	133.3	195.9
Subject 20	104.8	114.5	109.1	102.7	107.3	114.1	131.3	124.3	111.5	132.0	131.0
Subject 21	92.8	85.7	94.8	86.6	109.1	188.2	206.5	432.0	98.6	204.9	270.9

Subject 22	103.9	88.6	98.5	105.9	100.9	103.4	138.1	145.1	141.2	137.0	122.8
Subject 23	141.8	152.8	108.2	119.6	98.3	133.7	121.2	193.5	188.1	204.7	148.6
Subject 24	68.2	82.8	101.4	106.2	111.3	151.1	207.7	227.2	213.8	214.4	262.2
Median	**107.1**	**109.3**	**104.3**	**107.2**	**112.8**	**132.8**	**190.5**	**187.9**	**167.3**	**209.6**	**188.2**

Values of the exponent *n* for fore-and-aft vibration with a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	1.29	1.65	1.45	1.16	1.04	0.87	0.77	0.41	0.82	0.51	0.86
Subject 2	1.05	0.57	1.10	1.62	1.13	0.76	0.90	0.35	0.78	0.80	0.78
Subject 3	0.99	0.74	0.58	0.67	0.56	0.48	0.12	0.33	0.34	0.38	0.56
Subject 4	0.38	1.61	2.06	1.66	2.04	1.82	0.91	0.72	1.21	0.64	0.20
Subject 5	0.38	0.37	0.24	0.26	0.52	0.46	0.24	0.23	0.33	0.24	0.30
Subject 6	0.50	1.02	0.68	0.98	1.10	1.02	0.76	0.62	0.51	0.68	0.38
Subject 7	0.85	0.44	0.56	0.71	0.73	0.56	0.42	0.51	0.36	0.26	0.49
Subject 8	1.16	0.88	1.34	1.08	0.54	0.50	0.54	0.56	0.41	0.65	0.72
Subject 9	0.38	0.66	0.43	0.49	0.45	0.63	0.29	0.46	0.30	0.21	0.34
Subject 10	0.53	0.17	0.57	0.54	0.36	0.36	0.39	0.09	0.15	0.18	0.18

Subject 11	0.26	0.47	0.33	0.84	0.30	0.47	0.33	0.39	0.62	0.51	0.54
Subject 12	1.17	1.13	1.14	1.30	1.39	1.01	0.52	0.61	1.01	0.78	0.74
Subject 13	0.55	0.63	0.77	0.68	0.72	0.87	0.43	0.47	0.46	0.27	0.82
Subject 14	0.26	0.29	0.18	0.38	0.43	0.40	0.07	0.25	0.22	0.14	0.20
Subject 15	0.39	0.43	0.31	0.28	0.32	0.21	0.30	0.11	0.11	0.24	0.22
Subject 16	0.27	0.30	0.25	0.31	0.25	0.24	0.34	0.18	0.11	0.15	0.17
Subject 17	0.33	0.45	0.23	0.35	0.14	0.16	0.07	0.19	0.15	0.25	0.24
Subject 18	0.71	1.49	1.60	1.29	1.62	1.12	0.60	0.62	0.36	0.24	-0.33
Subject 19	0.19	0.14	0.18	0.08	0.45	0.17	0.27	0.18	0.09	0.18	0.07
Subject 20	0.12	0.24	0.22	0.14	0.13	0.20	0.15	0.17	0.08	0.11	0.11
Subject 21	0.91	1.36	0.99	0.93	1.10	0.06	0.50	0.13	0.18	0.31	0.31
Subject 22	0.52	0.38	0.33	0.33	0.41	0.23	0.33	0.41	0.26	0.28	0.22
Subject 23	0.78	0.90	0.86	1.15	0.98	0.55	0.86	0.77	0.40	0.70	0.31
Subject 24	0.33	0.54	0.73	0.72	0.80	0.73	0.47	0.41	0.30	0.26	0.45
Median	**0.51**	**0.56**	**0.57**	**0.69**	**0.55**	**0.49**	**0.40**	**0.40**	**0.33**	**0.26**	**0.31**

Values of the constant *k* for fore-and-aft vibration with a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	256.0	357.8	399.5	283.9	219.1	284.2	258.4	180.2	139.3	129.6	83.3
Subject 2	424.6	257.5	241.0	480.4	351.9	270.2	213.6	158.1	97.6	91.1	55.6
Subject 3	283.3	179.3	165.9	213.1	218.2	188.4	121.6	128.3	127.4	107.6	110.6
Subject 4	22.9	283.1	616.0	494.0	762.5	976.7	416.8	338.0	292.4	228.4	436.8
Subject 5	187.7	153.2	124.4	134.7	177.1	200.3	155.0	154.2	136.0	129.6	135.0
Subject 6	171.4	278.1	201.7	319.3	365.4	344.9	324.0	206.6	159.4	160.4	119.6
Subject 7	230.8	164.6	180.6	207.4	247.1	235.1	177.4	156.0	140.9	131.5	105.3
Subject 8	326.6	245.3	467.3	348.9	221.9	187.3	172.9	130.1	115.2	116.6	104.6
Subject 9	169.8	212.8	191.1	209.8	170.1	211.3	155.7	129.5	124.1	120.7	107.5
Subject 10	165.7	112.7	132.5	137.1	145.2	135.7	133.2	108.9	112.9	113.5	109.0
Subject 11	159.3	143.1	98.9	245.6	154.4	163.5	123.3	111.1	110.1	90.6	77.5
Subject 12	252.8	357.6	372.3	368.3	534.5	383.4	307.0	234.0	212.1	155.5	165.6
Subject 13	173.9	176.1	235.5	211.5	294.8	336.8	175.2	164.3	136.5	143.8	111.3
Subject 14	138.4	141.8	117.4	142.0	163.5	163.9	122.8	140.3	124.3	119.1	116.3
Subject 15	134.0	153.9	140.4	129.1	151.2	135.5	130.8	118.4	90.6	98.4	92.3

Subject 16	131.0	127.4	118.1	120.9	118.1	124.4	130.1	123.7	108.8	107.9	109.5
Subject 17	165.6	182.9	125.6	164.6	128.0	109.0	105.5	110.0	109.3	103.0	98.7
Subject 18	102.3	287.7	286.7	278.1	470.2	385.6	171.2	213.3	196.5	161.4	91.9
Subject 19	152.5	132.4	128.7	109.4	144.9	125.6	118.2	102.4	107.3	97.9	98.4
Subject 20	116.9	142.2	142.8	114.3	123.7	124.9	121.7	117.3	109.6	105.2	104.6
Subject 21	156.4	268.8	241.8	234.8	279.8	112.1	154.8	109.1	101.5	107.4	110.4
Subject 22	171.2	137.4	128.1	127.0	144.6	133.0	154.1	132.1	122.3	115.7	113.4
Subject 23	308.6	374.8	296.4	378.4	485.6	262.3	166.7	136.7	94.6	104.0	99.8
Subject 24	141.6	170.7	220.3	190.5	199.3	281.6	186.6	189.4	159.6	150.2	130.5
Median	**167.8**	**177.7**	**185.9**	**210.6**	**208.8**	**194.4**	**155.4**	**134.4**	**123.2**	**116.1**	**108.2**

Values of the exponent *n* for lateral vibration with a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	1.70	1.61	1.76	1.63	1.19	1.22	0.58	0.74	0.63	1.07	1.00
Subject 2	1.08	1.21	1.62	1.09	1.32	1.10	1.33	1.33	0.54	0.73	1.02
Subject 3	0.81	0.80	0.61	0.65	0.51	0.31	0.26	0.52	0.25	0.23	0.45
Subject 4	0.00	0.81	1.92	2.23	1.71	1.72	1.11	0.75	0.92	0.54	0.56

Subject 5	0.39	0.45	0.70	0.57	0.35	0.29	0.36	0.33	0.29	0.33	0.27
Subject 6	1.10	0.92	1.30	0.98	0.98	0.77	0.76	0.64	0.55	0.41	0.82
Subject 7	0.87	0.49	0.75	0.55	0.46	0.56	0.81	0.36	0.47	0.31	0.61
Subject 8	0.65	0.90	0.82	0.72	0.58	0.67	0.65	1.00	0.52	0.40	0.45
Subject 9	0.47	0.49	0.60	0.61	0.47	0.40	0.46	0.40	0.32	0.36	0.39
Subject 10	0.44	0.55	0.55	0.61	0.51	0.13	0.30	0.30	0.15	0.15	0.15
Subject 11	1.03	0.35	0.53	0.83	0.49	0.47	0.41	0.56	0.27	0.36	0.46
Subject 12	1.73	1.54	1.69	1.46	1.27	1.52	0.35	1.18	0.95	1.21	0.51
Subject 13	0.64	0.64	0.64	0.71	0.52	0.66	0.41	0.50	0.65	0.37	0.58
Subject 14	0.35	0.27	0.26	0.36	0.43	0.26	0.38	0.33	0.17	0.16	0.27
Subject 15	0.59	0.58	0.50	0.33	0.18	0.37	0.49	0.21	0.18	0.17	0.17
Subject 16	0.20	0.24	0.42	0.30	0.28	0.28	0.21	0.27	0.10	0.11	0.21
Subject 17	0.31	0.21	0.22	0.21	0.13	0.27	0.18	0.11	0.31	0.11	0.30
Subject 18	1.53	1.12	1.26	1.17	0.74	1.08	1.02	0.81	1.17	1.10	1.16
Subject 19	0.27	0.27	0.10	0.31	0.13	0.19	0.53	0.17	0.12	0.10	0.15
Subject 20	0.15	0.19	0.15	0.03	0.13	0.12	0.49	0.20	0.13	0.20	0.21
Subject 21	0.86	1.36	0.70	0.67	0.50	0.22	0.31	0.37	0.54	0.13	0.17

Subject 22	0.37	0.58	0.29	0.60	0.39	0.33	0.31	0.39	0.17	0.26	0.29
Subject 23	0.54	0.61	1.18	0.89	0.81	0.65	0.73	0.65	0.80	0.91	0.50
Subject 24	0.57	0.80	0.81	0.68	0.88	0.58	0.89	0.42	0.43	0.85	0.51
Median	**0.58**	**0.60**	**0.67**	**0.66**	**0.50**	**0.44**	**0.47**	**0.41**	**0.38**	**0.35**	**0.45**

Values of the constant *k* for lateral vibration with a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	466.0	379.3	600.2	495.3	351.0	313.8	194.8	183.1	160.4	100.7	71.1
Subject 2	336.4	370.3	595.0	471.5	470.4	230.0	246.0	198.7	141.0	75.1	53.2
Subject 3	197.4	229.8	178.5	195.3	193.0	153.6	129.2	148.3	135.3	128.0	134.0
Subject 4	15.4	40.4	1249.8	805.2	695.7	492.6	418.3	236.4	238.3	205.3	333.0
Subject 5	161.8	139.6	219.1	213.7	175.7	152.9	164.4	138.2	134.0	128.0	133.7
Subject 6	293.9	177.4	460.5	397.5	335.3	259.0	230.3	215.8	163.0	144.2	117.9
Subject 7	237.5	160.5	259.5	215.8	170.0	191.6	186.0	136.3	126.6	121.6	112.9
Subject 8	199.6	270.6	335.2	259.9	224.9	194.8	172.8	167.3	149.0	131.0	107.1
Subject 9	178.9	174.7	229.1	229.9	182.8	136.2	128.7	123.2	131.8	118.3	112.4
Subject 10	155.4	172.3	168.5	181.0	150.6	106.3	115.0	107.6	112.9	108.8	109.6

Subject 11	285.8	136.7	169.9	219.5	175.7	163.4	137.5	143.6	145.5	126.1	104.7
Subject 12	751.6	511.8	663.9	383.7	488.8	292.6	183.1	270.7	163.1	117.7	190.3
Subject 13	200.6	195.2	188.3	253.8	209.7	201.6	131.2	180.4	160.6	152.6	144.8
Subject 14	136.6	129.8	136.0	155.7	168.9	134.5	154.8	139.2	126.3	115.9	114.8
Subject 15	167.6	165.7	151.9	132.2	130.1	152.5	132.6	111.4	107.1	98.7	92.3
Subject 16	112.3	118.6	152.7	146.7	131.2	118.9	117.9	118.6	109.6	115.3	112.4
Subject 17	142.2	119.9	137.5	127.8	126.2	130.1	123.0	113.0	126.6	105.0	110.8
Subject 18	461.7	277.6	387.9	403.1	383.2	338.1	291.4	155.3	178.3	123.2	109.9
Subject 19	148.8	138.4	127.9	148.2	121.3	102.2	106.7	104.5	104.0	103.5	101.0
Subject 20	115.5	126.7	126.1	105.5	127.9	125.4	118.9	115.0	113.0	106.7	95.5
Subject 21	178.8	367.6	193.9	196.6	167.0	130.4	123.0	131.0	101.6	116.5	127.6
Subject 22	136.7	201.8	146.6	218.2	159.0	144.8	129.0	135.6	114.6	121.2	113.8
Subject 23	223.0	214.7	548.0	299.8	230.9	164.7	194.1	172.9	110.2	139.0	103.2
Subject 24	134.5	182.9	237.6	217.5	238.0	192.9	179.0	143.3	142.3	120.7	132.6
Median	**178.8**	**176.0**	**206.5**	**217.9**	**179.3**	**158.5**	**146.1**	**141.3**	**132.9**	**119.5**	**112.4**

Appendix D

Values of the exponent *n* for vertical vibration with a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	1.75	1.53	1.79	1.76	1.71	1.63	1.28	1.14	1.36	1.09	1.17
Subject 2	1.76	1.44	1.65	1.40	1.67	1.77	1.42	1.57	1.23	1.29	0.91
Subject 3	1.47	0.65	0.75	1.16	1.02	0.68	0.42	0.41	0.43	0.54	0.65
Subject 4	1.00	0.38	0.35	1.71	0.28	0.97	1.72	1.96	2.03	0.66	-0.15
Subject 5	0.66	0.61	0.51	0.63	0.48	0.43	0.54	0.45	0.25	0.26	0.38
Subject 6	1.28	1.00	1.28	1.16	1.48	1.63	1.67	1.49	0.80	0.91	0.90
Subject 7	0.52	0.85	1.26	0.77	1.05	0.99	1.61	0.76	0.31	0.83	0.71
Subject 8	0.94	1.32	0.28	1.17	0.91	1.17	1.31	1.06	0.79	1.13	1.00
Subject 9	0.54	0.48	0.62	0.32	0.62	0.58	0.49	0.49	0.22	0.46	0.44
Subject 10	0.36	0.27	0.30	0.30	0.25	0.21	0.61	0.21	0.42	0.68	0.65
Subject 11	0.92	0.87	1.07	1.01	1.39	1.54	1.11	0.60	0.93	0.33	1.12
Subject 12	1.98	1.67	1.61	1.41	1.40	1.77	0.48	0.98	1.05	1.12	1.07
Subject 13	0.79	0.94	0.51	0.70	0.08	0.73	1.07	0.59	0.34	0.54	0.60
Subject 14	0.38	0.26	0.29	0.52	0.32	0.18	0.41	0.27	0.28	0.21	0.34
Subject 15	0.55	0.64	0.48	0.40	0.37	0.46	0.44	0.20	0.02	0.45	0.32

Subject 16	0.42	0.40	0.29	0.23	0.37	0.28	0.25	0.27	0.23	0.24	0.16
Subject 17	0.30	0.28	0.23	0.21	0.18	0.20	0.19	0.24	0.15	0.15	0.24
Subject 18	1.65	1.02	1.61	1.53	1.36	2.34	1.07	1.66	0.82	1.15	-0.22
Subject 19	0.54	0.33	0.38	0.37	0.49	0.19	0.29	0.43	0.21	0.16	0.13
Subject 20	0.20	0.24	0.27	0.21	0.28	0.26	0.32	0.21	0.11	0.18	0.21
Subject 21	1.44	1.09	1.42	0.80	1.32	1.53	0.97	0.45	0.61	0.50	0.27
Subject 22	0.40	0.57	0.39	0.32	0.49	0.62	0.63	0.44	0.16	0.47	0.20
Subject 23	0.95	1.00	1.09	0.76	1.04	0.79	0.02	0.55	0.76	0.79	1.20
Subject 24	0.68	0.72	0.77	0.72	0.89	1.18	1.20	0.92	0.51	0.33	0.59
Median	**0.74**	**0.69**	**0.56**	**0.74**	**0.75**	**0.76**	**0.62**	**0.52**	**0.43**	**0.52**	**0.51**

Values of the constant *k* for vertical vibration with a beanbag											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0
Subject 1	72.5	105.3	110.5	118.0	182.6	343.2	439.3	377.9	441.1	407.4	226.9
Subject 2	101.1	114.8	113.5	139.2	276.0	416.1	399.2	588.5	451.4	252.4	141.5
Subject 3	70.9	95.2	101.6	91.8	142.9	166.2	173.9	177.0	170.7	218.0	253.4
Subject 4	57.3	14.0	25.9	87.5	21.3	63.1	423.2	785.1	1121.5	519.9	177.4

Appendix D

Subject 5	132.1	142.0	128.7	129.5	111.9	135.3	190.9	188.4	134.7	145.2	200.1
Subject 6	55.1	59.6	79.9	92.8	133.4	268.8	401.7	543.8	188.1	201.4	290.3
Subject 7	108.6	125.4	92.9	131.8	152.4	186.4	487.8	323.0	139.8	238.2	217.0
Subject 8	105.7	108.6	75.7	109.9	111.2	189.3	385.1	289.2	306.1	362.8	340.4
Subject 9	117.9	109.1	106.7	92.4	116.1	141.7	148.5	192.4	139.4	164.8	152.8
Subject 10	113.0	109.1	106.3	102.2	99.9	114.4	149.6	119.7	140.3	154.4	186.1
Subject 11	139.5	117.6	102.9	96.1	139.0	212.2	301.6	207.5	282.8	157.3	340.2
Subject 12	172.9	134.0	148.1	145.2	147.9	254.7	405.6	373.0	282.3	265.5	361.6
Subject 13	136.8	120.0	118.4	146.0	148.4	205.3	371.2	293.9	156.5	196.1	230.9
Subject 14	114.6	101.1	94.6	113.3	113.0	115.9	157.6	142.9	155.7	121.0	159.9
Subject 15	110.5	98.5	94.4	99.9	102.5	115.7	153.1	134.8	88.3	165.7	110.2
Subject 16	113.3	102.4	105.8	109.6	111.2	109.5	111.2	124.0	128.9	129.7	123.3
Subject 17	115.6	109.4	102.0	106.1	100.9	105.5	112.9	139.9	123.6	119.7	124.9
Subject 18	158.5	94.1	159.0	178.8	194.3	420.3	264.7	692.6	320.3	222.5	30.6
Subject 19	119.1	101.8	102.2	102.7	113.4	104.8	122.9	147.8	119.9	117.1	98.1
Subject 20	108.8	110.5	111.5	105.5	106.9	120.8	140.7	138.4	123.6	121.4	128.8
Subject 21	108.8	88.4	90.5	87.3	106.5	189.7	223.3	153.2	191.7	165.6	162.9

Subject 22	115.3	115.8	105.5	120.0	120.9	134.2	196.7	166.6	131.7	165.4	117.8
Subject 23	191.2	114.3	163.0	132.1	175.6	190.5	34.1	181.6	213.4	174.2	355.6
Subject 24	74.7	73.3	93.4	94.9	112.8	142.8	225.0	294.2	214.9	126.2	193.0
Median	**113.1**	**108.8**	**104.2**	**107.8**	**114.8**	**154.5**	**210.0**	**190.4**	**163.6**	**165.6**	**181.8**

D.4 Experiment presented in Chapter 7 – Individual participant alpha values for each motion.

Individual α values for single-axis stimuli												
Stimulus	*x*2, *x*4	*x*2, *x*8	*x*4, *x*8	*x*2, *x*4, *x*8	*y*2, *y*4	*y*2, *y*8	*y*4, *y*8	*y*2, *y*4, *y*8	*z*2, *z*4	*z*2, *z*8	*z*4, *z*8	*z*2, *z*4, *z*8
Subject 1	1.91	∞	2.51	3.68	2.21	∞	∞	3.20	2.88	2.17	∞	∞
Subject 2	3.11	2.18	2.18	2.71	2.44	1.94	3.94	2.16	∞	1.85	4.06	3.97
Subject 3	1.26	3.76	2.11	2.17	1.26	2.11	∞	∞	5.88	5.88	3.11	4.92
Subject 4	2.27	3.43	1.36	2.00	2.29	1.93	∞	3.14	1.14	1.06	1.41	2.27
Subject 5	1.12	∞	∞	3.8	∞	2.56	2.44	∞	∞	∞	∞	2.59
Subject 6	2.16	<1.00	1.10	3.1	∞	1.09	1.54	<1.00	<1.00	∞	∞	1.61
Subject 7	5.34	5.24	3.81	2.74	3.87	5.64	∞	2.95	2.48	∞	3.04	5.28
Subject 8	2.55	∞	2.39	2.40	3.83	2.25	1.51	2.07	∞	∞	1.82	∞
Subject 9	1.64	∞	∞	2.93	1.61	6.00	∞	1.88	1.10	<1.00	∞	2.57
Subject 10	6.00	∞	3.80	2.34	∞	3.11	3.11	2.46	2.49	3.43	2.97	2.66
Subject 11	∞	∞	1.87	∞	1.00	1.00	<1.00	1.61	1.61	<1.00	1.06	<1.00

Subject 12	∞	1.18	1.72	2.20	1.20	<1.00	4.21	1.72	<1.00	1.42	1.22	1.53
Subject 13	∞	1.48	2.54	2.10	∞	2.08	∞	3.04	4.08	1.34	∞	3.35
Subject 14	<1.00	<1.00	∞	<1.00	<1.00	1.37	1.42	<1.00	<1.00	<1.00	<1.00	1
Subject 15	<1.00	∞	1.66	1.83	2.55	∞	1.19	1.64	∞	1.79	2.29	∞
Subject 16	1.88	1.97	2.43	2.10	1.78	1.91	∞	3.75	2.54	<1.00	∞	1.2
Subject 17	2.57	∞	1.21	3.31	4.53	5.39	∞	4.49	1.87	∞	∞	3.26
Subject 18	1.90	∞	2.41	2.36	1.37	1.37	∞	2.03	∞	∞	3.80	3.44

Individual α values for dual-axis stimuli									
Stimulus	*x2, y2*	*x2, y4*	*x2, y8*	*x4, y2*	*x4, y4*	*x4, y8*	*x8, y2*	*x8, y4*	*x8, y8*
Subject 1	1.95	∞	∞	∞	∞	2.00	∞	∞	5.13
Subject 2	1.48	2.11	1.48	1.82	3.11	1.77	2.44	6.58	4.26
Subject 3	1.11	1.71	∞	1.94	2.44	2.11	∞	∞	3.80
Subject 4	2.10	1.94	2.50	1.59	∞	2.04	2.29	∞	∞
Subject 5	1.39	1.12	1.76	1.83	2.23	1.48	∞	∞	∞

Subject 6	1.24	1.56	1	1.76	1.61	1.24	1.00	∞	1.23
Subject 7	2.23	2.16	3.80	3.10	1.92	2.51	4.16	9.76	2.96
Subject 8	∞	∞	∞	2.11	∞	2.25	∞	∞	1.05
Subject 9	3.11	15.03	2.05	2.02	2.71	<1	1.50	∞	1.20
Subject 10	2.39	1.68	1.68	2.49	2.49	1.91	∞	∞	3.31
Subject 11	2.78	∞	1.24	2.00	1.51	∞	1.14	1.21	<1
Subject 12	<1	1.00	1.10	1.19	2.02	2.22	1.41	2.33	2.54
Subject 13	3.15	∞	1.28	5.69	∞	∞	∞	4.15	∞
Subject 14	<1	<1	<1	<1	1	2.39	<1	1.37	1.53
Subject 15	∞	∞	<1	1.00	1.04	1.08	∞	∞	2.51
Subject 16	1.55	∞	1.97	2.91	4.57	4.88	1.91	∞	2.27
Subject 17	∞	4.15	2.62	2.11	2.57	2.83	1.97	∞	2.62
Subject 18	∞	3.46	1.62	1.32	2.24	1.73	∞	∞	2.24

Individual α values for dual-axis stimuli									
Stimulus	*x2, z2*	*x2, z4*	*x2, z8*	*x4, z2*	*x4, z4*	*x4, z8*	*x8, z2*	*x8, z4*	*x8, z8*
Subject 1	∞	∞	∞	3.80	∞	∞	3.19	2.41	2.93
Subject 2	4.21	2.44	2.00	2.55	2.44	2.00	2.64	∞	∞
Subject 3	2.18	3.11	3.11	1.48	1.48	1.82	∞	2.49	3.76
Subject 4	1.46	1.42	3.08	1.89	∞	1.14	∞	1.54	∞
Subject 5	2.17	1.03	1.34	9.06	1.28	2.23	∞	∞	∞
Subject 6	∞	1.71	∞	<1	<1	<1	<1	1.48	<1
Subject 7	2.03	2	5.17	5.66	1.75	1.89	4.91	3.79	3.58
Subject 8	∞	∞	∞	4.91	∞	1.66	∞	∞	1.49
Subject 9	1.88	∞	∞	∞	∞	∞	<1	1.20	∞
Subject 10	2	1.71	1.87	∞	∞	1.82	∞	∞	∞
Subject 11	1.68	∞	∞	<1	2.60	1	∞	∞	<1
Subject 12	<1	∞	1.12	1.77	1.19	1.30	1.09	1.18	2.03
Subject 13	∞	3.95	2.53	∞	∞	∞	2.25	2.72	1.04

Subject 14	<1	<1	<1	<1	<1	<1	<1	<1	<1
Subject 15	∞	1.29	<1	∞	1.30	1.20	∞	∞	∞
Subject 16	1.12	<1	<1	∞	1.80	∞	1.68	∞	∞
Subject 17	∞	∞	∞	1	∞	∞	2.87	2.20	6.62
Subject 18	∞	∞	2.27	∞	1.62	∞	∞	∞	∞

Individual α values for dual-axis stimuli									
Stimulus	*y*2, *z*2	*y*2, *z*4	*y*2, *z*8	*y*4, *z*2	*y*4, *z*4	*y*4, *z*8	*y*8, *z*2	*y*8, *z*4	*y*8, *z*8
Subject 1	2.29	∞	∞	1.69	3.61	∞	∞	2.46	3.06
Subject 2	2.19	2.90	1.62	1.98	3.94	∞	3.23	2.90	2.24
Subject 3	2.44	2.44	2.44	3.11	3.11	∞	∞	∞	∞
Subject 4	1.51	1.46	1.06	∞	∞	1.58	1.44	∞	∞
Subject 5	∞	2.35	6.52	3.11	1.56	∞	6.07	∞	∞
Subject 6	<1	<1	<1	3.00	∞	∞	<1	2.06	1.13
Subject 7	8.49	2.25	4.40	2.63	∞	3.60	2.63	2.22	2.31

Subject 8	4.91	∞	∞	∞	∞	∞	∞	3.69	1.19
Subject 9	2.33	∞	∞	∞	∞	2.78	1.39	1.71	1.19
Subject 10	2.10	∞	2	2.10	∞	2.00	∞	1.68	∞
Subject 11	1.00	2.10	<1	<1	1.61	<1	<1	1.06	1
Subject 12	<1	<1	1.12	1.11	1.60	2.34	1.22	1.10	1.46
Subject 13	∞	∞	∞	∞	∞	∞	1.29	1.28	1.17
Subject 14	<1	∞	<1	<1	<1	∞	∞	∞	∞
Subject 15	∞	1.16	2.53	<1	2.29	2.16	∞	∞	∞
Subject 16	∞	∞	<1	∞	∞	<1	∞	∞	1.24
Subject 17	1.82	∞	1.82	∞	∞	∞	∞	∞	3.16
Subject 18	2.49	3.80	3.80	∞	2.08	1.37	2.78	3.68	2.61

Individual α values for tri-axial stimuli										
Stimulus	*x2, y2, z2*	*x2, y2, z4*	*x2, y2, z8*	*x2, y4, z2*	*x2, y4, z4*	*x2, y4, z8*	*x2, y8, z2*	*x2, y8, z4*	*x2, y8, z8*	*x2, y2, z2*
Subject 1	1.91	∞	2.51	3.68	2.21	∞	∞	3.20	2.88	2.17

Appendix D

Subject 2	3.11	2.18	2.18	2.71	2.44	1.94	3.94	2.16	∞	1.85
Subject 3	1.26	3.76	2.11	2.17	1.26	2.11	∞	∞	5.88	5.88
Subject 4	2.27	3.43	1.36	2.00	2.29	1.93	∞	3.14	1.14	1.06
Subject 5	1.12	∞	∞	3.8	∞	2.56	2.44	∞	∞	∞
Subject 6	2.16	<1.00	1.10	3.1	∞	1.09	1.54	<1.00	<1.00	∞
Subject 7	5.34	5.24	3.81	2.74	3.87	5.64	∞	2.95	2.48	∞
Subject 8	2.55	∞	2.39	2.40	3.83	2.25	1.51	2.07	∞	∞
Subject 9	1.64	∞	∞	2.93	1.61	6.00	∞	1.88	1.10	<1.00
Subject 10	6.00	∞	3.80	2.34	∞	3.11	3.11	2.46	2.49	3.43
Subject 11	∞	∞	1.87	∞	1.00	1.00	<1.00	1.61	1.61	<1.00
Subject 12	∞	1.18	1.72	2.20	1.20	<1.00	4.21	1.72	<1.00	1.42
Subject 13	∞	1.48	2.54	2.10	∞	2.08	∞	3.04	4.08	1.34
Subject 14	<1.00	<1.00	∞	<1.00	<1.00	1.37	1.42	<1.00	<1.00	<1.00
Subject 15	<1.00	∞	1.66	1.83	2.55	∞	1.19	1.64	∞	1.79
Subject 16	1.88	1.97	2.43	2.10	1.78	1.91	∞	3.75	2.54	<1.00

Subject 17	2.57	∞	1.21	3.31	4.53	5.39	∞	4.49	1.87	∞
Subject 18	1.90	∞	2.41	2.36	1.37	1.37	∞	2.03	∞	∞

D.5 Experiment presented in Chapter 7 – Magnitude estimates of each stimulus for each participant.

Normalised results are such that the median magnitude estimate of each session for each participant was equal to 100.

Participant 1							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	250	200	200	200	182	133	182
x 4, *y* 2, *z* 2	225	200	200	180	182	133	180
x 8, *y* 2, *z* 2	200	150	175	160	136	117	136
y 2, *z* 2	150	200	200	120	182	133	133
x 2, *y* 4, *z* 2	150	150	200	120	136	133	133
x 4, *y* 4, *z* 2	175	125	150	140	114	100	114
x 8, *y* 4, *z* 2	80	110	150	64	100	100	100
y 4, *z* 2	175	200	150	140	182	100	140
x 2, *y* 8, *z* 2	125	175	150	100	159	100	100
x 4, *y* 8, *z* 2	150	100	150	120	91	100	100
x 8, *y* 8, *z* 2	100	80	100	80	73	67	73
y 8, *z* 2	150	50	80	120	45	53	53
x 2, *z* 2	150	90	150	120	82	100	100
x 4, *z* 2	175	125	130	140	114	87	114
x 8, *z* 2	100	100	75	80	91	50	80
z 2	120	75	75	96	68	50	68
x 2, *y* 2, *z* 4	200	150	200	160	136	133	136
x 4, *y* 2, *z* 4	200	180	200	160	164	133	160
x 8, *y* 2, *z* 4	225	110	200	180	100	133	133

y 2, *z* 4	125	150	150	100	136	100	100
x 2, *y* 4, *z* 4	100	200	225	80	182	150	150
x 4, *y* 4, *z* 4	200	125	150	160	114	100	114
x 8, *y* 4, *z* 4	200	100	150	160	91	100	100
y 4, *z* 4	150	120	175	120	109	117	117
x 2, *y* 8, *z* 4	120	80	220	96	73	147	96
x 4, *y* 8, *z* 4	125	100	150	100	91	100	100
x 8, *y* 8, *z* 4	100	90	100	80	82	67	80
y 8, *z* 4	75	100	110	60	91	73	73
x 2, *z* 4	75	110	150	60	100	100	100
x 4, *z* 4	125	110	180	100	100	120	100
x 8, *z* 4	100	100	120	80	91	80	80
z 4	75	60	150	60	55	100	60
x 2, *y* 2, *z* 8	200	200	200	160	182	133	160
x 4, *y* 2, *z* 8	200	130	200	160	118	133	133
x 8, *y* 2, *z* 8	100	75	150	80	68	100	80
y 2, *z* 8	125	100	200	100	91	133	100
x 2, *y* 4, *z* 8	125	175	175	100	159	117	117
x 4, *y* 4, *z* 8	200	100	175	160	91	117	117
x 8, *y* 4, *z* 8	125	100	175	100	91	117	100
y 4, *z* 8	125	100	120	100	91	80	91
x 2, *y* 8, *z* 8	100	100	110	80	91	73	80
x 4, *y* 8, *z* 8	125	100	150	100	91	100	100
x 8, *y* 8, *z* 8	75	90	120	60	82	80	80
y 8, *z* 8	75	50	100	60	45	67	60
x 2, *z* 8	100	125	100	80	114	67	80

x 4, *z* 8	150	100	100	120	91	67	91
x 8, *z* 8	85	80	70	68	73	47	68
z 8	50	50	80	40	45	53	45
x 2, *y* 2	200	200	250	160	182	167	167
x 4, *y* 2	225	125	180	180	114	120	120
x 8, *y* 2	125	150	125	100	136	83	100
y 2	150	150	180	120	136	120	120
x 2, *y* 4	175	100	160	140	91	107	107
x 4, *y* 4	100	125	220	80	114	147	114
x 8, *y* 4	125	90	120	100	82	80	82
y 4	100	125	175	80	114	117	114
x 2, *y* 8	100	110	180	80	100	120	100
x 4, *y* 8	150	150	175	120	136	117	120
x 8, *y* 8	80	70	120	64	64	80	64
y 8	50	90	75	40	82	50	50
x 2	150	125	100	120	114	67	114
x 4	125	120	175	100	109	117	109
x 8	75	60	100	60	55	67	60
x 2, *x* 4	200	150	250	160	136	167	160
x 2, *x* 8	150	125	125	120	114	83	114
x 4, *x* 8	150	130	125	120	118	83	118
x 2, *x* 4, *x* 8	300	150	200	240	136	133	136
y 2, *y* 4	200	200	200	160	182	133	160
y 2, *y* 8	200	110	175	160	100	117	117
y 4, *y* 8	100	120	150	80	109	100	100
y 2, *y* 4, *y* 8	125	180	220	100	164	147	147

z 2, *z* 4	75	90	150	60	82	100	82
z 2, *z* 8	100	90	80	80	82	53	80
z 4, *z* 8	75	60	110	60	55	73	60
z 2, *z* 4, *z* 8	75	75	125	60	68	83	68

Participant 2							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	120	80	110	120	80	122	120
x 4, *y* 2, *z* 2	140	120	120	140	120	133	133
x 8, *y* 2, *z* 2	120	120	100	120	120	111	120
y 2, *z* 2	110	110	100	110	110	111	110
x 2, *y* 4, *z* 2	140	130	110	140	130	122	130
x 4, *y* 4, *z* 2	120	140	120	120	140	133	133
x 8, *y* 4, *z* 2	120	110	110	120	110	122	120
y 4, *z* 2	120	110	110	120	110	122	120
x 2, *y* 8, *z* 2	120	120	130	120	120	144	120
x 4, *y* 8, *z* 2	140	120	80	140	120	89	120
x 8, *y* 8, *z* 2	100	100	90	100	100	100	100
y 8, *z* 2	110	100	80	110	100	89	100
x 2, *z* 2	110	80	90	110	80	100	100
x 4, *z* 2	120	110	100	120	110	111	111
x 8, *z* 2	100	110	100	100	110	111	110
z 2	80	90	80	80	90	89	89
x 2, *y* 2, *z* 4	110	110	120	110	110	133	110
x 4, *y* 2, *z* 4	100	100	80	100	100	89	100

x 8, *y* 2, *z* 4	110	110	100	110	110	111	110
y 2, *z* 4	70	90	80	70	90	89	89
x 2, *y* 4, *z* 4	110	100	100	110	100	111	110
x 4, *y* 4, *z* 4	90	90	100	90	90	111	90
x 8, *y* 4, *z* 4	100	100	80	100	100	89	100
y 4, *z* 4	90	110	70	90	110	78	90
x 2, *y* 8, *z* 4	110	100	100	110	100	111	110
x 4, *y* 8, *z* 4	120	110	90	120	110	100	110
x 8, *y* 8, *z* 4	100	120	100	100	120	111	111
y 8, *z* 4	80	100	80	80	100	89	89
x 2, *z* 4	90	100	100	90	100	111	100
x 4, *z* 4	100	80	90	100	80	100	100
x 8, *z* 4	80	80	90	80	80	100	80
z 4	70	60	90	70	60	100	70
x 2, *y* 2, *z* 8	120	130	110	120	130	122	122
x 4, *y* 2, *z* 8	120	120	110	120	120	122	120
x 8, *y* 2, *z* 8	100	100	100	100	100	111	100
y 2, *z* 8	90	100	90	90	100	100	100
x 2, *y* 4, *z* 8	110	110	100	110	110	111	110
x 4, *y* 4, *z* 8	110	100	100	110	100	111	110
x 8, *y* 4, *z* 8	90	100	100	90	100	111	100
y 4, *z* 8	80	80	90	80	80	100	80
x 2, *y* 8, *z* 8	120	100	80	120	100	89	100
x 4, *y* 8, *z* 8	110	100	90	110	100	100	100
x 8, *y* 8, *z* 8	90	110	70	90	110	78	90
y 8, *z* 8	80	90	80	80	90	89	89

x 2, *z* 8	100	100	100	100	100	111	100
x 4, *z* 8	100	100	90	100	100	100	100
x 8, *z* 8	80	80	90	80	80	100	80
z 8	60	60	60	60	60	67	60
x 2, *y* 2	100	120	120	100	120	133	120
x 4, *y* 2	110	100	100	110	100	111	110
x 8, *y* 2	100	100	70	100	100	78	100
y 2	70	60	80	70	60	89	70
x 2, *y* 4	130	110	100	130	110	111	111
x 4, *y* 4	80	100	100	80	100	111	100
x 8, *y* 4	100	80	80	100	80	89	89
y 4	70	80	80	70	80	89	80
x 2, *y* 8	120	120	80	120	120	89	120
x 4, *y* 8	120	100	100	120	100	111	111
x 8, *y* 8	80	90	80	80	90	89	89
y 8	70	60	70	70	60	78	70
x 2	80	80	60	80	80	67	80
x 4	80	80	80	80	80	89	80
x 8	100	80	70	100	80	78	80
x 2, *x* 4	80	100	110	80	100	122	100
x 2, *x* 8	100	110	100	100	110	111	110
x 4, *x* 8	110	110	90	110	110	100	110
x 2, *x* 4, *x* 8	120	110	120	120	110	133	120
y 2, *y* 4	90	100	90	90	100	100	100
y 2, *y* 8	80	100	100	80	100	111	100
y 4, *y* 8	90	80	90	90	80	100	90

y 2, *y* 4, *y* 8	110	130	110	110	130	122	122
z 2, *z* 4	70	80	70	70	80	78	78
z 2, *z* 8	110	90	100	110	90	111	110
z 4, *z* 8	70	90	70	70	90	78	78
z 2, *z* 4, *z* 8	80	100	100	80	100	111	100

Participant 3							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	160	160	130	145	145	118	145
x 4, *y* 2, *z* 2	130	140	100	118	127	91	118
x 8, *y* 2, *z* 2	100	130	110	91	118	100	100
y 2, *z* 2	100	110	100	91	100	91	91
x 2, *y* 4, *z* 2	110	120	160	100	109	145	109
x 4, *y* 4, *z* 2	120	160	140	109	145	127	127
x 8, *y* 4, *z* 2	80	90	100	73	82	91	82
y 4, *z* 2	100	100	100	91	91	91	91
x 2, *y* 8, *z* 2	140	130	100	127	118	91	118
x 4, *y* 8, *z* 2	150	120	150	136	109	136	136
x 8, *y* 8, *z* 2	130	120	100	118	109	91	109
y 8, *z* 2	90	100	80	82	91	73	82
x 2, *z* 2	110	110	110	100	100	100	100
x 4, *z* 2	100	120	120	91	109	109	109
x 8, *z* 2	140	100	80	127	91	73	91
z 2	60	100	80	55	91	73	73
x 2, *y* 2, *z* 4	120	130	120	109	118	109	109

x 4, *y* 2, *z* 4	130	130	130	118	118	118	118
x 8, *y* 2, *z* 4	120	110	120	109	100	109	109
y 2, *z* 4	110	100	90	100	91	82	91
x 2, *y* 4, *z* 4	150	150	130	136	136	118	136
x 4, *y* 4, *z* 4	120	100	120	109	91	109	109
x 8, *y* 4, *z* 4	130	100	120	118	91	109	109
y 4, *z* 4	120	100	100	109	91	91	91
x 2, *y* 8, *z* 4	150	140	130	136	127	118	127
x 4, *y* 8, *z* 4	120	120	130	109	109	118	109
x 8, *y* 8, *z* 4	120	140	120	109	127	109	109
y 8, *z* 4	80	110	100	73	100	91	91
x 2, *z* 4	90	100	120	82	91	109	91
x 4, *z* 4	120	110	140	109	100	127	109
x 8, *z* 4	110	120	120	100	109	109	109
z 4	60	80	100	55	73	91	73
x 2, *y* 2, *z* 8	160	140	140	145	127	127	127
x 4, *y* 2, *z* 8	170	130	170	155	118	155	155
x 8, *y* 2, *z* 8	80	140	140	73	127	127	127
y 2, *z* 8	100	100	120	91	91	109	91
x 2, *y* 4, *z* 8	130	110	130	118	100	118	118
x 4, *y* 4, *z* 8	160	110	120	145	100	109	109
x 8, *y* 4, *z* 8	80	90	100	73	82	91	82
y 4, *z* 8	70	80	100	64	73	91	73
x 2, *y* 8, *z* 8	160	120	130	145	109	118	118
x 4, *y* 8, *z* 8	130	110	100	118	100	91	100
x 8, *y* 8, *z* 8	120	150	120	109	136	109	109

y 8, *z* 8	130	100	90	118	91	82	91
x 2, *z* 8	100	100	90	91	91	82	91
x 4, *z* 8	90	110	130	82	100	118	100
x 8, *z* 8	100	140	110	91	127	100	100
z 8	70	90	80	64	82	73	73
x 2, *y* 2	100	140	140	91	127	127	127
x 4, *y* 2	100	140	80	91	127	73	91
x 8, *y* 2	90	90	90	82	82	82	82
y 2	70	110	60	64	100	55	64
x 2, *y* 4	110	120	130	100	109	118	109
x 4, *y* 4	140	100	100	127	91	91	91
x 8, *y* 4	100	120	90	91	109	82	91
y 4	60	80	90	55	73	82	73
x 2, *y* 8	100	140	100	91	127	91	91
x 4, *y* 8	140	120	120	127	109	109	109
x 8, *y* 8	130	120	110	118	109	100	109
y 8	100	80	100	91	73	91	91
x 2	100	70	80	91	64	73	73
x 4	90	60	70	82	55	64	64
x 8	80	100	100	73	91	91	91
x 2, *x* 4	130	130	100	118	118	91	118
x 2, *x* 8	110	100	130	100	91	118	100
x 4, *x* 8	120	990	80	109	900	73	109
x 2, *x* 4, *x* 8	140	110	150	127	100	136	127
y 2, *y* 4	120	130	130	109	118	118	118
y 2, *y* 8	100	130	120	91	118	109	109

y 4, *y* 8	70	100	90	64	91	82	82
y 2, *y* 4, *y* 8	100	100	130	91	91	118	91
z 2, *z* 4	90	90	90	82	82	82	82
z 2, *z* 8	90	100	80	82	91	73	82
z 4, *z* 8	120	100	100	109	91	91	91
z 2, *z* 4, *z* 8	100	110	100	91	100	91	91

Participant 4							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	150	150	150	100	125	125	125
x 4, *y* 2, *z* 2	100	100	120	67	83	100	83
x 8, *y* 2, *z* 2	150	150	120	100	125	100	100
y 2, *z* 2	150	100	100	100	83	83	83
x 2, *y* 4, *z* 2	175	160	150	117	133	125	125
x 4, *y* 4, *z* 2	120	120	100	80	100	83	83
x 8, *y* 4, *z* 2	120	120	120	80	100	100	100
y 4, *z* 2	100	100	100	67	83	83	83
x 2, *y* 8, *z* 2	200	150	120	133	125	100	125
x 4, *y* 8, *z* 2	150	120	150	100	100	125	100
x 8, *y* 8, *z* 2	150	120	120	100	100	100	100
y 8, *z* 2	100	150	150	67	125	125	125
x 2, *z* 2	120	120	120	80	100	100	100
x 4, *z* 2	120	90	100	80	75	83	80
x 8, *z* 2	100	120	80	67	100	67	67
z 2	50	50	60	33	42	50	42

x 2, *y* 2, *z* 4	200	150	120	133	125	100	125
x 4, *y* 2, *z* 4	150	150	150	100	125	125	125
x 8, *y* 2, *z* 4	150	120	150	100	100	125	100
y 2, *z* 4	150	100	100	100	83	83	83
x 2, *y* 4, *z* 4	150	120	150	100	100	125	100
x 4, *y* 4, *z* 4	150	150	150	100	125	125	125
x 8, *y* 4, *z* 4	160	150	175	107	125	146	125
y 4, *z* 4	175	100	100	117	83	83	83
x 2, *y* 8, *z* 4	200	175	120	133	146	100	133
x 4, *y* 8, *z* 4	150	150	150	100	125	125	125
x 8, *y* 8, *z* 4	100	150	120	67	125	100	100
y 8, *z* 4	120	150	120	80	125	100	100
x 2, *z* 4	150	150	90	100	125	75	100
x 4, *z* 4	100	120	75	67	100	63	67
x 8, *z* 4	150	150	120	100	125	100	100
z 4	60	75	30	40	63	25	40
x 2, *y* 2, *z* 8	150	150	150	100	125	125	125
x 4, *y* 2, *z* 8	150	150	150	100	125	125	125
x 8, *y* 2, *z* 8	175	120	150	117	100	125	117
y 2, *z* 8	100	150	120	67	125	100	100
x 2, *y* 4, *z* 8	175	175	120	117	146	100	117
x 4, *y* 4, *z* 8	150	150	120	100	125	100	100
x 8, *y* 4, *z* 8	150	150	120	100	125	100	100
y 4, *z* 8	150	120	75	100	100	63	100
x 2, *y* 8, *z* 8	150	150	150	100	125	125	125
x 4, *y* 8, *z* 8	200	150	150	133	125	125	125

x 8, *y* 8, *z* 8	100	175	150	67	146	125	125
y 8, *z* 8	175	120	100	117	100	83	100
x 2, *z* 8	130	75	100	87	63	83	83
x 4, *z* 8	150	150	100	100	125	83	100
x 8, *z* 8	100	140	100	67	117	83	83
z 8	50	50	75	33	42	63	42
x 2, *y* 2	160	120	50	107	100	42	100
x 4, *y* 2	150	120	120	100	100	100	100
x 8, *y* 2	150	120	100	100	100	83	100
y 2	50	90	75	33	75	63	63
x 2, *y* 4	175	120	150	117	100	125	117
x 4, *y* 4	100	120	100	67	100	83	83
x 8, *y* 4	100	120	50	67	100	42	67
y 4	80	100	120	53	83	100	83
x 2, *y* 8	200	150	150	133	125	125	125
x 4, *y* 8	150	150	150	100	125	125	125
x 8, *y* 8	150	120	120	100	100	100	100
y 8	160	100	150	107	83	125	107
x 2	120	90	100	80	75	83	80
x 4	100	100	80	67	83	67	67
x 8	75	100	100	50	83	83	83
x 2, *x* 4	150	150	120	100	125	100	100
x 2, *x* 8	100	120	120	67	100	100	100
x 4, *x* 8	150	150	150	100	125	125	125
x 2, *x* 4, *x* 8	200	175	150	133	146	125	133
y 2, *y* 4	150	100	120	100	83	100	100

y 2, *y* 8	150	150	150	100	125	125	125
y 4, *y* 8	150	150	120	100	125	100	100
y 2, *y* 4, *y* 8	150	175	150	100	146	125	125
z 2, *z* 4	60	80	100	40	67	83	67
z 2, *z* 8	120	75	100	80	63	83	80
z 4, *z* 8	175	80	60	117	67	50	67
z 2, *z* 4, *z* 8	100	80	80	67	67	67	67

Participant 5							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	120	70	100	109	64	100	100
x 4, *y* 2, *z* 2	110	120	130	100	109	130	109
x 8, *y* 2, *z* 2	80	120	100	73	109	100	100
y 2, *z* 2	80	80	70	73	73	70	73
x 2, *y* 4, *z* 2	90	120	80	82	109	80	82
x 4, *y* 4, *z* 2	90	130	140	82	118	140	118
x 8, *y* 4, *z* 2	100	120	90	91	109	90	91
y 4, *z* 2	110	110	150	100	100	150	100
x 2, *y* 8, *z* 2	120	70	110	109	64	110	109
x 4, *y* 8, *z* 2	110	150	110	100	136	110	110
x 8, *y* 8, *z* 2	100	120	100	91	109	100	100
y 8, *z* 2	130	90	85	118	82	85	85
x 2, *z* 2	95	125	50	86	114	50	86
x 4, *z* 2	95	140	80	86	127	80	86
x 8, *z* 2	90	120	110	82	109	110	109

z 2	110	70	80	100	64	80	80
x 2, *y* 2, *z* 4	95	130	110	86	118	110	110
x 4, *y* 2, *z* 4	120	140	120	109	127	120	120
x 8, *y* 2, *z* 4	115	120	100	105	109	100	105
y 2, *z* 4	110	90	90	100	82	90	90
x 2, *y* 4, *z* 4	105	110	90	95	100	90	95
x 4, *y* 4, *z* 4	90	130	120	82	118	120	118
x 8, *y* 4, *z* 4	90	150	110	82	136	110	110
y 4, *z* 4	100	110	105	91	100	105	100
x 2, *y* 8, *z* 4	115	90	95	105	82	95	95
x 4, *y* 8, *z* 4	110	130	110	100	118	110	110
x 8, *y* 8, *z* 4	115	100	100	105	91	100	100
y 8, *z* 4	70	120	70	64	109	70	70
x 2, *z* 4	80	120	80	73	109	80	80
x 4, *z* 4	100	120	120	91	109	120	109
x 8, *z* 4	50	110	100	45	100	100	100
z 4	100	50	30	91	45	30	45
x 2, *y* 2, *z* 8	110	120	70	100	109	70	100
x 4, *y* 2, *z* 8	110	130	95	100	118	95	100
x 8, *y* 2, *z* 8	130	90	90	118	82	90	90
y 2, *z* 8	110	90	90	100	82	90	90
x 2, *y* 4, *z* 8	120	120	100	109	109	100	109
x 4, *y* 4, *z* 8	125	100	110	114	91	110	110
x 8, *y* 4, *z* 8	90	90	120	82	82	120	82
y 4, *z* 8	150	85	75	136	77	75	77
x 2, *y* 8, *z* 8	100	95	110	91	86	110	91

x 4, *y* 8, *z* 8	100	100	130	91	91	130	91
x 8, *y* 8, *z* 8	80	130	90	73	118	90	90
y 8, *z* 8	70	80	90	64	73	90	73
x 2, *z* 8	120	80	100	109	73	100	100
x 4, *z* 8	120	120	90	109	109	90	109
x 8, *z* 8	130	110	110	118	100	110	110
z 8	90	85	80	82	77	80	80
x 2, *y* 2	110	110	85	100	100	85	100
x 4, *y* 2	130	110	120	118	100	120	118
x 8, *y* 2	80	90	100	73	82	100	82
y 2	90	90	40	82	82	40	82
x 2, *y* 4	120	130	90	109	118	90	109
x 4, *y* 4	130	120	90	118	109	90	109
x 8, *y* 4	120	105	120	109	95	120	109
y 4	120	60	80	109	55	80	80
x 2, *y* 8	110	90	80	100	82	80	82
x 4, *y* 8	130	150	120	118	136	120	120
x 8, *y* 8	110	80	100	100	73	100	100
y 8	120	50	70	109	45	70	70
x 2	130	40	30	118	36	30	36
x 4	120	70	80	109	64	80	80
x 8	130	110	110	118	100	110	110
x 2, *x* 4	80	120	115	73	109	115	109
x 2, *x* 8	80	90	100	73	82	100	82
x 4, *x* 8	120	130	110	109	118	110	110
x 2, *x* 4, *x* 8	80	130	130	73	118	130	118

y 2, *y* 4	90	80	110	82	73	110	82
y 2, *y* 8	120	110	100	109	100	100	100
y 4, *y* 8	140	90	100	127	82	100	100
y 2, *y* 4, *y* 8	80	120	80	73	109	80	80
z 2, *z* 4	70	85	80	64	77	80	77
z 2, *z* 8	70	80	70	64	73	70	70
z 4, *z* 8	120	65	80	109	59	80	80
z 2, *z* 4, *z* 8	120	130	70	109	118	70	109

Participant 6							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	120	500	400	80	143	200	143
x 4, *y* 2, *z* 2	120	800	700	80	229	350	229
x 8, *y* 2, *z* 2	150	600	150	100	171	75	100
y 2, *z* 2	100	500	300	67	143	150	143
x 2, *y* 4, *z* 2	250	800	500	167	229	250	229
x 4, *y* 4, *z* 2	150	700	300	100	200	150	150
x 8, *y* 4, *z* 2	250	150	200	167	43	100	100
y 4, *z* 2	170	400	400	113	114	200	114
x 2, *y* 8, *z* 2	300	750	600	200	214	300	214
x 4, *y* 8, *z* 2	250	550	200	167	157	100	157
x 8, *y* 8, *z* 2	170	300	100	113	86	50	86
y 8, *z* 2	150	400	150	100	114	75	100
x 2, *z* 2	150	350	300	100	100	150	100
x 4, *z* 2	200	500	300	133	143	150	143

x 8, *z* 2	150	250	50	100	71	25	71
z 2	50	200	20	33	57	10	33
x 2, *y* 2, *z* 4	250	600	400	167	171	200	171
x 4, *y* 2, *z* 4	220	250	400	147	71	200	147
x 8, *y* 2, *z* 4	150	300	150	100	86	75	86
y 2, *z* 4	200	200	75	133	57	38	57
x 2, *y* 4, *z* 4	300	400	400	200	114	200	200
x 4, *y* 4, *z* 4	300	500	500	200	143	250	200
x 8, *y* 4, *z* 4	150	300	150	100	86	75	86
y 4, *z* 4	170	150	300	113	43	150	113
x 2, *y* 8, *z* 4	200	600	400	133	171	200	171
x 4, *y* 8, *z* 4	220	500	200	147	143	100	143
x 8, *y* 8, *z* 4	120	200	200	80	57	100	80
y 8, *z* 4	100	200	100	67	57	50	57
x 2, *z* 4	160	400	200	107	114	100	107
x 4, *z* 4	200	500	250	133	143	125	133
x 8, *z* 4	100	150	50	67	43	25	43
z 4	70	100	20	47	29	10	29
x 2, *y* 2, *z* 8	200	800	500	133	229	250	229
x 4, *y* 2, *z* 8	250	300	600	167	86	300	167
x 8, *y* 2, *z* 8	150	400	100	100	114	50	100
y 2, *z* 8	120	200	75	80	57	38	57
x 2, *y* 4, *z* 8	350	600	300	233	171	150	171
x 4, *y* 4, *z* 8	200	500	200	133	143	100	133
x 8, *y* 4, *z* 8	170	400	600	113	114	300	114
y 4, *z* 8	150	400	80	100	114	40	100

x 2, *y* 8, *z* 8	200	400	500	133	114	250	133
x 4, *y* 8, *z* 8	150	500	500	100	143	250	143
x 8, *y* 8, *z* 8	120	400	80	80	114	40	80
y 8, *z* 8	120	200	80	80	57	40	57
x 2, *z* 8	150	200	400	100	57	200	100
x 4, *z* 8	200	600	500	133	171	250	171
x 8, *z* 8	150	100	80	100	29	40	40
z 8	50	20	20	33	6	10	10
x 2, *y* 2	140	400	500	93	114	250	114
x 4, *y* 2	220	300	150	147	86	75	86
x 8, *y* 2	120	80	100	80	23	50	50
y 2	80	80	50	53	23	25	25
x 2, *y* 4	250	700	100	167	200	50	167
x 4, *y* 4	200	600	300	133	171	150	150
x 8, *y* 4	100	500	100	67	143	50	67
y 4	170	150	400	113	43	200	113
x 2, *y* 8	250	500	300	167	143	150	150
x 4, *y* 8	150	400	300	100	114	150	114
x 8, *y* 8	100	100	300	67	29	150	67
y 8	50	200	100	33	57	50	50
x 2	150	400	50	100	114	25	100
x 4	120	150	400	80	43	200	80
x 8	100	20	50	67	6	25	25
x 2, *x* 4	200	200	250	133	57	125	125
x 2, *x* 8	200	300	400	133	86	200	133
x 4, *x* 8	200	200	200	133	57	100	100

x 2, *x* 4, *x* 8	130	400	500	87	114	250	114
y 2, *y* 4	150	250	200	100	71	100	100
y 2, *y* 8	170	250	100	113	71	50	71
y 4, *y* 8	200	300	300	133	86	150	133
y 2, *y* 4, *y* 8	200	700	500	133	200	250	200
z 2, *z* 4	150	150	150	100	43	75	75
z 2, *z* 8	80	50	50	53	14	25	25
z 4, *z* 8	120	100	50	80	29	25	29
z 2, *z* 4, *z* 8	100	100	100	67	29	50	50

Participant 7							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	150	160	150	150	145	130	145
x 4, *y* 2, *z* 2	150	135	150	150	123	130	130
x 8, *y* 2, *z* 2	80	125	125	80	114	109	109
y 2, *z* 2	70	130	110	70	118	96	96
x 2, *y* 4, *z* 2	130	140	135	130	127	117	127
x 4, *y* 4, *z* 2	120	100	145	120	91	126	120
x 8, *y* 4, *z* 2	120	110	90	120	100	78	100
y 4, *z* 2	105	98	110	105	89	96	96
x 2, *y* 8, *z* 2	85	110	115	85	100	100	100
x 4, *y* 8, *z* 2	110	125	120	110	114	104	110
x 8, *y* 8, *z* 2	90	105	100	90	95	87	90
y 8, *z* 2	110	85	110	110	77	96	96
x 2, *z* 2	115	115	100	115	105	87	105

x 4, *z* 2	90	95	105	90	86	91	90
x 8, *z* 2	70	95	100	70	86	87	86
z 2	60	75	85	60	68	74	68
x 2, *y* 2, *z* 4	140	150	145	140	136	126	136
x 4, *y* 2, *z* 4	145	125	135	145	114	117	117
x 8, *y* 2, *z* 4	110	105	135	110	95	117	110
y 2, *z* 4	95	125	125	95	114	109	109
x 2, *y* 4, *z* 4	120	135	120	120	123	104	120
x 4, *y* 4, *z* 4	125	135	140	125	123	122	123
x 8, *y* 4, *z* 4	100	115	120	100	105	104	104
y 4, *z* 4	70	80	125	70	73	109	73
x 2, *y* 8, *z* 4	100	140	130	100	127	113	113
x 4, *y* 8, *z* 4	95	110	125	95	100	109	100
x 8, *y* 8, *z* 4	95	95	130	95	86	113	95
y 8, *z* 4	95	105	115	95	95	100	95
x 2, *z* 4	100	110	105	100	100	91	100
x 4, *z* 4	110	95	140	110	86	122	110
x 8, *z* 4	110	95	95	110	86	83	86
z 4	60	55	85	60	50	74	60
x 2, *y* 2, *z* 8	130	145	135	130	132	117	130
x 4, *y* 2, *z* 8	140	140	125	140	127	109	127
x 8, *y* 2, *z* 8	130	120	135	130	109	117	117
y 2, *z* 8	100	110	125	100	100	109	100
x 2, *y* 4, *z* 8	120	140	125	120	127	109	120
x 4, *y* 4, *z* 8	135	120	150	135	109	130	130
x 8, *y* 4, *z* 8	100	105	130	100	95	113	100

y 4, *z* 8	90	95	125	90	86	109	90
x 2, *y* 8, *z* 8	100	100	120	100	91	104	100
x 4, *y* 8, *z* 8	125	100	125	125	91	109	109
x 8, *y* 8, *z* 8	110	130	115	110	118	100	110
y 8, *z* 8	90	110	125	90	100	109	100
x 2, *z* 8	70	95	100	70	86	87	86
x 4, *z* 8	130	100	130	130	91	113	113
x 8, *z* 8	100	95	105	100	86	91	91
z 8	85	70	80	85	64	70	70
x 2, *y* 2	120	115	145	120	105	126	120
x 4, *y* 2	145	125	115	145	114	100	114
x 8, *y* 2	105	115	115	105	105	100	105
y 2	95	105	85	95	95	74	95
x 2, *y* 4	115	120	115	115	109	100	109
x 4, *y* 4	120	130	130	120	118	113	118
x 8, *y* 4	85	95	95	85	86	83	85
y 4	65	90	90	65	82	78	78
x 2, *y* 8	95	85	115	95	77	100	95
x 4, *y* 8	105	120	125	105	109	109	109
x 8, *y* 8	100	125	110	100	114	96	100
y 8	80	85	90	80	77	78	78
x 2	80	97	50	80	88	43	80
x 4	70	95	125	70	86	109	86
x 8	80	85	95	80	77	83	80
x 2, *x* 4	95	130	90	95	118	78	95
x 2, *x* 8	100	100	105	100	91	91	91

x 4, *x* 8	110	110	110	110	100	96	100
x 2, *x* 4, *x* 8	135	135	140	135	123	122	123
y 2, *y* 4	105	115	125	105	105	109	105
y 2, *y* 8	110	105	115	110	95	100	100
y 4, *y* 8	75	95	100	75	86	87	86
y 2, *y* 4, *y* 8	125	135	135	125	123	117	123
z 2, *z* 4	85	95	92	85	86	80	85
z 2, *z* 8	80	80	85	80	73	74	74
z 4, *z* 8	60	90	95	60	82	83	82
z 2, *z* 4, *z* 8	80	90	100	80	82	87	82

Participant 8							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	250	200	300	167	100	150	150
x 4, *y* 2, *z* 2	200	300	280	133	150	140	140
x 8, *y* 2, *z* 2	190	200	200	127	100	100	100
y 2, *z* 2	150	220	220	100	110	110	110
x 2, *y* 4, *z* 2	200	300	280	133	150	140	140
x 4, *y* 4, *z* 2	200	200	220	133	100	110	110
x 8, *y* 4, *z* 2	200	250	220	133	125	110	125
y 4, *z* 2	160	180	200	107	90	100	100
x 2, *y* 8, *z* 2	200	250	250	133	125	125	125
x 4, *y* 8, *z* 2	200	200	220	133	100	110	110
x 8, *y* 8, *z* 2	150	200	200	100	100	100	100
y 8, *z* 2	100	180	150	67	90	75	75

x 2, *z* 2	150	180	220	100	90	110	100
x 4, *z* 2	200	220	200	133	110	100	110
x 8, *z* 2	80	120	220	53	60	110	60
z 2	180	200	170	120	100	85	100
x 2, *y* 2, *z* 4	250	250	280	167	125	140	140
x 4, *y* 2, *z* 4	200	280	250	133	140	125	133
x 8, *y* 2, *z* 4	120	180	220	80	90	110	90
y 2, *z* 4	150	180	150	100	90	75	90
x 2, *y* 4, *z* 4	150	250	250	100	125	125	125
x 4, *y* 4, *z* 4	150	200	220	100	100	110	100
x 8, *y* 4, *z* 4	90	220	180	60	110	90	90
y 4, *z* 4	100	130	180	67	65	90	67
x 2, *y* 8, *z* 4	150	200	250	100	100	125	100
x 4, *y* 8, *z* 4	170	250	200	113	125	100	113
x 8, *y* 8, *z* 4	100	180	200	67	90	100	90
y 8, *z* 4	80	100	150	53	50	75	53
x 2, *z* 4	190	150	200	127	75	100	100
x 4, *z* 4	150	180	150	100	90	75	90
x 8, *z* 4	80	140	100	53	70	50	53
z 4	50	80	70	33	40	35	35
x 2, *y* 2, *z* 8	200	250	280	133	125	140	133
x 4, *y* 2, *z* 8	120	200	220	80	100	110	100
x 8, *y* 2, *z* 8	150	220	200	100	110	100	100
y 2, *z* 8	100	150	200	67	75	100	75
x 2, *y* 4, *z* 8	150	220	200	100	110	100	100
x 4, *y* 4, *z* 8	120	180	180	80	90	90	90

x 8, *y* 4, *z* 8	80	180	150	53	90	75	75
y 4, *z* 8	100	150	100	67	75	50	67
x 2, *y* 8, *z* 8	150	250	220	100	125	110	110
x 4, *y* 8, *z* 8	180	250	200	120	125	100	120
x 8, *y* 8, *z* 8	150	120	150	100	60	75	75
y 8, *z* 8	100	180	150	67	90	75	75
x 2, *z* 8	150	250	200	100	125	100	100
x 4, *z* 8	150	150	200	100	75	100	100
x 8, *z* 8	120	140	100	80	70	50	70
z 8	50	70	50	33	35	25	33
x 2, *y* 2	250	180	200	167	90	100	100
x 4, *y* 2	200	250	250	133	125	125	125
x 8, *y* 2	180	150	180	120	75	90	90
y 2	160	150	180	107	75	90	90
x 2, *y* 4	180	200	150	120	100	75	100
x 4, *y* 4	110	150	150	73	75	75	75
x 8, *y* 4	90	180	150	60	90	75	75
y 4	80	160	150	53	80	75	75
x 2, *y* 8	160	200	180	107	100	90	100
x 4, *y* 8	180	150	200	120	75	100	100
x 8, *y* 8	150	200	180	100	100	90	100
y 8	110	100	100	73	50	50	50
x 2	50	200	200	33	100	100	100
x 4	120	180	180	80	90	90	90
x 8	80	150	100	53	75	50	53
x 2, *x* 4	150	300	250	100	150	125	125

x 2, *x* 8	120	270	200	80	135	100	100
x 4, *x* 8	150	300	180	100	150	90	100
x 2, *x* 4, *x* 8	200	280	250	133	140	125	133
y 2, *y* 4	200	200	200	133	100	100	100
y 2, *y* 8	180	200	180	120	100	90	100
y 4, *y* 8	150	210	180	100	105	90	100
y 2, *y* 4, *y* 8	200	250	250	133	125	125	125
z 2, *z* 4	150	140	150	100	70	75	75
z 2, *z* 8	100	130	150	67	65	75	67
z 4, *z* 8	80	100	80	53	50	40	50
z 2, *z* 4, *z* 8	140	180	100	93	90	50	90

Participant 9							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	120	130	110	133	144	138	138
x 4, *y* 2, *z* 2	130	90	140	144	100	175	144
x 8, *y* 2, *z* 2	110	120	80	122	133	100	122
y 2, *z* 2	70	110	85	78	122	106	106
x 2, *y* 4, *z* 2	130	90	90	144	100	113	113
x 4, *y* 4, *z* 2	170	140	150	189	156	188	188
x 8, *y* 4, *z* 2	60	90	90	67	100	113	100
y 4, *z* 2	90	80	70	100	89	88	89
x 2, *y* 8, *z* 2	80	110	140	89	122	175	122
x 4, *y* 8, *z* 2	120	100	70	133	111	88	111
x 8, *y* 8, *z* 2	80	70	70	89	78	88	88

y 8, *z* 2	50	70	70	56	78	88	78
x 2, *z* 2	100	80	90	111	89	113	111
x 4, *z* 2	100	70	90	111	78	113	111
x 8, *z* 2	90	70	80	100	78	100	100
z 2	40	60	30	44	67	38	44
x 2, *y* 2, *z* 4	120	110	110	133	122	138	133
x 4, *y* 2, *z* 4	140	130	160	156	144	200	156
x 8, *y* 2, *z* 4	100	140	90	111	156	113	113
y 2, *z* 4	60	90	100	67	100	125	100
x 2, *y* 4, *z* 4	100	170	90	111	189	113	113
x 4, *y* 4, *z* 4	130	70	100	144	78	125	125
x 8, *y* 4, *z* 4	80	100	70	89	111	88	89
y 4, *z* 4	90	70	70	100	78	88	88
x 2, *y* 8, *z* 4	120	80	70	133	89	88	89
x 4, *y* 8, *z* 4	140	150	150	156	167	188	167
x 8, *y* 8, *z* 4	90	100	70	100	111	88	100
y 8, *z* 4	100	60	60	111	67	75	75
x 2, *z* 4	80	80	80	89	89	100	89
x 4, *z* 4	110	90	80	122	100	100	100
x 8, *z* 4	80	80	50	89	89	63	89
z 4	60	30	40	67	33	50	50
x 2, *y* 2, *z* 8	140	100	140	156	111	175	156
x 4, *y* 2, *z* 8	170	140	130	189	156	163	163
x 8, *y* 2, *z* 8	80	100	80	89	111	100	100
y 2, *z* 8	100	70	70	111	78	88	88
x 2, *y* 4, *z* 8	170	90	130	189	100	163	163

x 4, *y* 4, *z* 8	150	200	110	167	222	138	167
x 8, *y* 4, *z* 8	85	120	50	94	133	63	94
y 4, *z* 8	70	150	90	78	167	113	113
x 2, *y* 8, *z* 8	60	120	70	67	133	88	88
x 4, *y* 8, *z* 8	90	110	60	100	122	75	100
x 8, *y* 8, *z* 8	65	60	60	72	67	75	72
y 8, *z* 8	70	60	60	78	67	75	75
x 2, *z* 8	100	60	60	111	67	75	75
x 4, *z* 8	70	70	60	78	78	75	78
x 8, *z* 8	40	70	40	44	78	50	50
z 8	30	20	30	33	22	38	33
x 2, *y* 2	100	120	100	111	133	125	125
x 4, *y* 2	90	170	120	100	189	150	150
x 8, *y* 2	110	120	60	122	133	75	122
y 2	90	110	80	100	122	100	100
x 2, *y* 4	50	150	90	56	167	113	113
x 4, *y* 4	110	130	150	122	144	188	144
x 8, *y* 4	130	100	60	144	111	75	111
y 4	100	90	90	111	100	113	111
x 2, *y* 8	80	100	90	89	111	113	111
x 4, *y* 8	150	170	120	167	189	150	167
x 8, *y* 8	110	80	60	122	89	75	89
y 8	60	40	40	67	44	50	50
x 2	110	80	80	122	89	100	100
x 4	70	120	90	78	133	113	113
x 8	60	20	40	67	22	50	50

x 2, *x* 4	160	130	130	178	144	163	163
x 2, *x* 8	120	80	70	133	89	88	89
x 4, *x* 8	70	80	90	78	89	113	89
x 2, *x* 4, *x* 8	110	130	110	122	144	138	138
y 2, *y* 4	80	150	130	89	167	163	163
y 2, *y* 8	120	90	70	133	100	88	100
y 4, *y* 8	90	90	110	100	100	138	100
y 2, *y* 4, *y* 8	110	180	130	122	200	163	163
z 2, *z* 4	80	75	80	89	83	100	89
z 2, *z* 8	90	80	70	100	89	88	89
z 4, *z* 8	40	40	40	44	44	50	44
z 2, *z* 4, *z* 8	70	60	40	78	67	50	67

Participant 10							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	120	120	100	120	120	125	120
x 4, *y* 2, *z* 2	120	120	100	120	120	125	120
x 8, *y* 2, *z* 2	120	120	90	120	120	113	120
y 2, *z* 2	100	80	80	100	80	100	100
x 2, *y* 4, *z* 2	100	100	80	100	100	100	100
x 4, *y* 4, *z* 2	100	120	90	100	120	113	113
x 8, *y* 4, *z* 2	150	120	100	150	120	125	125
y 4, *z* 2	100	80	80	100	80	100	100
x 2, *y* 8, *z* 2	150	100	80	150	100	100	100
x 4, *y* 8, *z* 2	150	120	110	150	120	138	138

x 8, *y* 8, *z* 2	100	100	90	100	100	113	100
y 8, *z* 2	80	80	80	80	80	100	80
x 2, *z* 2	80	80	70	80	80	88	80
x 4, *z* 2	90	100	100	90	100	125	100
x 8, *z* 2	100	100	80	100	100	100	100
z 2	70	60	50	70	60	63	63
x 2, *y* 2, *z* 4	120	90	80	120	90	100	100
x 4, *y* 2, *z* 4	130	130	100	130	130	125	130
x 8, *y* 2, *z* 4	130	100	90	130	100	113	113
y 2, *z* 4	80	70	60	80	70	75	75
x 2, *y* 4, *z* 4	100	100	100	100	100	125	100
x 4, *y* 4, *z* 4	120	120	120	120	120	150	120
x 8, *y* 4, *z* 4	120	120	80	120	120	100	120
y 4, *z* 4	80	70	70	80	70	88	80
x 2, *y* 8, *z* 4	100	90	90	100	90	113	100
x 4, *y* 8, *z* 4	120	130	120	120	130	150	130
x 8, *y* 8, *z* 4	100	120	100	100	120	125	120
y 8, *z* 4	100	90	80	100	90	100	100
x 2, *z* 4	80	60	60	80	60	75	75
x 4, *z* 4	100	100	100	100	100	125	100
x 8, *z* 4	100	100	90	100	100	113	100
z 4	60	50	40	60	50	50	50
x 2, *y* 2, *z* 8	100	100	80	100	100	100	100
x 4, *y* 2, *z* 8	140	120	100	140	120	125	125
x 8, *y* 2, *z* 8	120	100	100	120	100	125	120
y 2, *z* 8	90	100	80	90	100	100	100

x 2, *y* 4, *z* 8	100	80	90	100	80	113	100
x 4, *y* 4, *z* 8	120	140	120	120	140	150	140
x 8, *y* 4, *z* 8	120	120	100	120	120	125	120
y 4, *z* 8	100	80	80	100	80	100	100
x 2, *y* 8, *z* 8	130	120	80	130	120	100	120
x 4, *y* 8, *z* 8	120	140	100	120	140	125	125
x 8, *y* 8, *z* 8	150	130	100	150	130	125	130
y 8, *z* 8	80	80	80	80	80	100	80
x 2, *z* 8	80	80	70	80	80	88	80
x 4, *z* 8	120	100	100	120	100	125	120
x 8, *z* 8	80	100	80	80	100	100	100
z 8	60	60	70	60	60	88	60
x 2, *y* 2	90	80	80	90	80	100	90
x 4, *y* 2	110	120	100	110	120	125	120
x 8, *y* 2	90	100	80	90	100	100	100
y 2	70	80	70	70	80	88	80
x 2, *y* 4	100	80	80	100	80	100	100
x 4, *y* 4	120	100	100	120	100	125	120
x 8, *y* 4	100	100	90	100	100	113	100
y 4	80	80	80	80	80	100	80
x 2, *y* 8	120	100	80	120	100	100	100
x 4, *y* 8	130	120	130	130	120	163	130
x 8, *y* 8	80	120	90	80	120	113	113
y 8	80	80	80	80	80	100	80
x 2	80	50	40	80	50	50	50
x 4	100	100	80	100	100	100	100

x 8	80	100	80	80	100	100	100
x 2, *x* 4	100	90	100	100	90	125	100
x 2, *x* 8	80	80	70	80	80	88	80
x 4, *x* 8	120	120	110	120	120	138	120
x 2, *x* 4, *x* 8	100	140	120	100	140	150	140
y 2, *y* 4	80	80	90	80	80	113	80
y 2, *y* 8	120	90	80	120	90	100	100
y 4, *y* 8	100	90	80	100	90	100	100
y 2, *y* 4, *y* 8	130	100	100	130	100	125	125
z 2, *z* 4	80	70	60	80	70	75	75
z 2, *z* 8	80	60	60	80	60	75	75
z 4, *z* 8	70	60	70	70	60	88	70
z 2, *z* 4, *z* 8	100	70	70	100	70	88	88

Participant 11							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	300	250	250	150	200	200	200
x 4, *y* 2, *z* 2	250	200	175	125	160	140	140
x 8, *y* 2, *z* 2	100	200	150	50	160	120	120
y 2, *z* 2	200	150	150	100	120	120	120
x 2, *y* 4, *z* 2	250	175	250	125	140	200	140
x 4, *y* 4, *z* 2	225	100	150	113	80	120	113
x 8, *y* 4, *z* 2	200	100	100	100	80	80	80
y 4, *z* 2	200	100	200	100	80	160	100
x 2, *y* 8, *z* 2	300	250	200	150	200	160	160

x 4, *y* 8, *z* 2	200	125	100	100	100	80	100
x 8, *y* 8, *z* 2	75	50	75	38	40	60	40
y 8, *z* 2	250	100	125	125	80	100	100
x 2, *z* 2	300	150	250	150	120	200	150
x 4, *z* 2	250	200	100	125	160	80	125
x 8, *z* 2	50	50	100	25	40	80	40
z 2	100	50	50	50	40	40	40
x 2, *y* 2, *z* 4	300	200	200	150	160	160	160
x 4, *y* 2, *z* 4	300	150	125	150	120	100	120
x 8, *y* 2, *z* 4	250	150	150	125	120	120	120
y 2, *z* 4	150	125	150	75	100	120	100
x 2, *y* 4, *z* 4	300	200	225	150	160	180	160
x 4, *y* 4, *z* 4	150	150	125	75	120	100	100
x 8, *y* 4, *z* 4	200	125	100	100	100	80	100
y 4, *z* 4	200	100	100	100	80	80	80
x 2, *y* 8, *z* 4	275	200	225	138	160	180	160
x 4, *y* 8, *z* 4	200	200	100	100	160	80	100
x 8, *y* 8, *z* 4	200	100	100	100	80	80	80
y 8, *z* 4	150	125	100	75	100	80	80
x 2, *z* 4	250	250	125	125	200	100	125
x 4, *z* 4	150	100	100	75	80	80	80
x 8, *z* 4	100	100	75	50	80	60	60
z 4	125	100	75	63	80	60	63
x 2, *y* 2, *z* 8	300	250	175	150	200	140	150
x 4, *y* 2, *z* 8	200	250	175	100	200	140	140
x 8, *y* 2, *z* 8	150	125	150	75	100	120	100

y 2, *z* 8	300	200	150	150	160	120	150
x 2, *y* 4, *z* 8	300	300	250	150	240	200	200
x 4, *y* 4, *z* 8	300	100	100	150	80	80	80
x 8, *y* 4, *z* 8	200	100	125	100	80	100	100
y 4, *z* 8	150	150	100	75	120	80	80
x 2, *y* 8, *z* 8	300	250	150	150	200	120	150
x 4, *y* 8, *z* 8	200	50	75	100	40	60	60
x 8, *y* 8, *z* 8	100	100	125	50	80	100	80
y 8, *z* 8	200	50	50	100	40	40	40
x 2, *z* 8	200	150	200	100	120	160	120
x 4, *z* 8	100	100	100	50	80	80	80
x 8, *z* 8	200	100	50	100	80	40	80
z 8	40	50	25	20	40	20	20
x 2, *y* 2	300	200	175	150	160	140	150
x 4, *y* 2	200	150	75	100	120	60	100
x 8, *y* 2	300	150	150	150	120	120	120
y 2	150	100	150	75	80	120	80
x 2, *y* 4	200	200	150	100	160	120	120
x 4, *y* 4	300	50	100	150	40	80	80
x 8, *y* 4	200	100	100	100	80	80	80
y 4	100	50	50	50	40	40	40
x 2, *y* 8	300	150	200	150	120	160	150
x 4, *y* 8	100	50	100	50	40	80	50
x 8, *y* 8	250	100	50	125	80	40	80
y 8	100	25	25	50	20	20	20
x 2	250	175	200	125	140	160	140

x 4	50	75	125	25	60	100	60
x 8	100	50	75	50	40	60	50
x 2, *x* 4	50	150	200	25	120	160	120
x 2, *x* 8	150	150	250	75	120	200	120
x 4, *x* 8	200	100	50	100	80	40	80
x 2, *x* 4, *x* 8	250	150	200	125	120	160	125
y 2, *y* 4	300	150	100	150	120	80	120
y 2, *y* 8	200	125	50	100	100	40	100
y 4, *y* 8	250	50	100	125	40	80	80
y 2, *y* 4, *y* 8	200	100	200	100	80	160	100
z 2, *z* 4	250	100	100	125	80	80	80
z 2, *z* 8	250	100	75	125	80	60	80
z 4, *z* 8	250	100	100	125	80	80	80
z 2, *z* 4, *z* 8	250	175	75	125	140	60	125

Participant 12							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	110	80	110	122	73	100	100
x 4, *y* 2, *z* 2	100	110	110	111	100	100	100
x 8, *y* 2, *z* 2	120	130	130	133	118	118	118
y 2, *z* 2	60	80	70	67	73	64	67
x 2, *y* 4, *z* 2	90	100	100	100	91	91	91
x 4, *y* 4, *z* 2	120	140	120	133	127	109	127
x 8, *y* 4, *z* 2	140	150	140	156	136	127	136
y 4, *z* 2	90	120	90	100	109	82	100

x 2, *y* 8, *z* 2	110	120	120	122	109	109	109
x 4, *y* 8, *z* 2	120	130	130	133	118	118	118
x 8, *y* 8, *z* 2	110	140	130	122	127	118	122
y 8, *z* 2	80	110	110	89	100	100	100
x 2, *z* 2	60	70	70	67	64	64	64
x 4, *z* 2	80	100	120	89	91	109	91
x 8, *z* 2	140	140	130	156	127	118	127
z 2	30	50	30	33	45	27	33
x 2, *y* 2, *z* 4	70	60	70	78	55	64	64
x 4, *y* 2, *z* 4	100	120	120	111	109	109	109
x 8, *y* 2, *z* 4	110	120	120	122	109	109	109
y 2, *z* 4	60	90	70	67	82	64	67
x 2, *y* 4, *z* 4	100	110	100	111	100	91	100
x 4, *y* 4, *z* 4	100	140	120	111	127	109	111
x 8, *y* 4, *z* 4	130	130	130	144	118	118	118
y 4, *z* 4	70	90	100	78	82	91	82
x 2, *y* 8, *z* 4	90	100	120	100	91	109	100
x 4, *y* 8, *z* 4	110	140	140	122	127	127	127
x 8, *y* 8, *z* 4	130	140	150	144	127	136	136
y 8, *z* 4	80	110	110	89	100	100	100
x 2, *z* 4	60	30	30	67	27	27	27
x 4, *z* 4	70	110	110	78	100	100	100
x 8, *z* 4	130	110	130	144	100	118	118
z 4	20	30	30	22	27	27	27
x 2, *y* 2, *z* 8	80	100	90	89	91	82	89
x 4, *y* 2, *z* 8	100	130	110	111	118	100	111

x 8, *y* 2, *z* 8	110	140	130	122	127	118	122
y 2, *z* 8	60	90	70	67	82	64	67
x 2, *y* 4, *z* 8	100	100	100	111	91	91	91
x 4, *y* 4, *z* 8	120	120	120	133	109	109	109
x 8, *y* 4, *z* 8	130	130	120	144	118	109	118
y 4, *z* 8	90	90	90	100	82	82	82
x 2, *y* 8, *z* 8	90	130	110	100	118	100	100
x 4, *y* 8, *z* 8	130	120	130	144	109	118	118
x 8, *y* 8, *z* 8	120	120	140	133	109	127	127
y 8, *z* 8	120	90	110	133	82	100	100
x 2, *z* 8	60	60	80	67	55	73	67
x 4, *z* 8	110	120	110	122	109	100	109
x 8, *z* 8	120	120	110	133	109	100	109
z 8	40	40	60	44	36	55	44
x 2, *y* 2	50	30	80	56	27	73	56
x 4, *y* 2	70	120	110	78	109	100	100
x 8, *y* 2	100	120	140	111	109	127	111
y 2	20	30	30	22	27	27	27
x 2, *y* 4	90	110	110	100	100	100	100
x 4, *y* 4	90	120	130	100	109	118	109
x 8, *y* 4	110	120	130	122	109	118	118
y 4	60	80	90	67	73	82	73
x 2, *y* 8	90	110	110	100	100	100	100
x 4, *y* 8	100	120	110	111	109	100	109
x 8, *y* 8	120	130	120	133	118	109	118
y 8	70	70	110	78	64	100	78

x 2	30	20	30	33	18	27	27
x 4	80	90	90	89	82	82	82
x 8	110	90	110	122	82	100	100
x 2, *x* 4	70	80	90	78	73	82	78
x 2, *x* 8	110	130	120	122	118	109	118
x 4, *x* 8	140	150	120	156	136	109	136
x 2, *x* 4, *x* 8	130	140	140	144	127	127	127
y 2, *y* 4	80	100	100	89	91	91	91
y 2, *y* 8	90	120	120	100	109	109	109
y 4, *y* 8	80	90	130	89	82	118	89
y 2, *y* 4, *y* 8	130	110	130	144	100	118	118
z 2, *z* 4	40	70	80	44	64	73	64
z 2, *z* 8	60	70	70	67	64	64	64
z 4, *z* 8	70	70	50	78	64	45	64
z 2, *z* 4, *z* 8	70	80	80	78	73	73	73

Participant 13							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	70	120	130	64	109	130	109
x 4, *y* 2, *z* 2	120	150	100	109	136	100	109
x 8, *y* 2, *z* 2	110	100	110	100	91	110	100
y 2, *z* 2	100	100	90	91	91	90	91
x 2, *y* 4, *z* 2	140	120	90	127	109	90	109
x 4, *y* 4, *z* 2	130	130	140	118	118	140	118
x 8, *y* 4, *z* 2	140	100	90	127	91	90	91

y 4, *z* 2	100	100	90	91	91	90	91
x 2, *y* 8, *z* 2	130	90	90	118	82	90	90
x 4, *y* 8, *z* 2	140	130	120	127	118	120	120
x 8, *y* 8, *z* 2	150	130	100	136	118	100	118
y 8, *z* 2	90	80	90	82	73	90	82
x 2, *z* 2	80	70	90	73	64	90	73
x 4, *z* 2	100	120	140	91	109	140	109
x 8, *z* 2	100	120	80	91	109	80	91
z 2	50	50	30	45	45	30	45
x 2, *y* 2, *z* 4	120	140	90	109	127	90	109
x 4, *y* 2, *z* 4	100	160	170	91	145	170	145
x 8, *y* 2, *z* 4	160	120	100	145	109	100	109
y 2, *z* 4	140	90	80	127	82	80	82
x 2, *y* 4, *z* 4	110	130	90	100	118	90	100
x 4, *y* 4, *z* 4	130	130	150	118	118	150	118
x 8, *y* 4, *z* 4	150	120	100	136	109	100	109
y 4, *z* 4	75	100	100	68	91	100	91
x 2, *y* 8, *z* 4	120	100	80	109	91	80	91
x 4, *y* 8, *z* 4	90	150	140	82	136	140	136
x 8, *y* 8, *z* 4	100	90	90	91	82	90	90
y 8, *z* 4	100	80	90	91	73	90	90
x 2, *z* 4	75	90	100	68	82	100	82
x 4, *z* 4	100	110	130	91	100	130	100
x 8, *z* 4	100	120	80	91	109	80	91
z 4	60	75	50	55	68	50	55
x 2, *y* 2, *z* 8	70	100	110	64	91	110	91

x 4, *y* 2, *z* 8	130	180	120	118	164	120	120
x 8, *y* 2, *z* 8	120	120	100	109	109	100	109
y 2, *z* 8	130	85	70	118	77	70	77
x 2, *y* 4, *z* 8	120	100	120	109	91	120	109
x 4, *y* 4, *z* 8	120	140	150	109	127	150	127
x 8, *y* 4, *z* 8	130	110	130	118	100	130	118
y 4, *z* 8	110	100	80	100	91	80	91
x 2, *y* 8, *z* 8	100	90	100	91	82	100	91
x 4, *y* 8, *z* 8	140	110	150	127	100	150	127
x 8, *y* 8, *z* 8	120	90	90	109	82	90	90
y 8, *z* 8	100	80	70	91	73	70	73
x 2, *z* 8	80	90	80	73	82	80	80
x 4, *z* 8	160	130	110	145	118	110	118
x 8, *z* 8	120	110	110	109	100	110	109
z 8	20	40	30	18	36	30	30
x 2, *y* 2	140	100	130	127	91	130	127
x 4, *y* 2	130	160	160	118	145	160	145
x 8, *y* 2	90	130	130	82	118	130	118
y 2	80	130	120	73	118	120	118
x 2, *y* 4	130	100	100	118	91	100	100
x 4, *y* 4	180	150	130	164	136	130	136
x 8, *y* 4	120	120	100	109	109	100	109
y 4	130	110	100	118	100	100	100
x 2, *y* 8	110	130	110	100	118	110	110
x 4, *y* 8	120	150	130	109	136	130	130
x 8, *y* 8	130	90	80	118	82	80	82

y 8	50	70	50	45	64	50	50
x 2	70	85	80	64	77	80	77
x 4	110	150	140	100	136	140	136
x 8	110	90	80	100	82	80	82
x 2, *x* 4	110	140	150	100	127	150	127
x 2, *x* 8	120	140	130	109	127	130	127
x 4, *x* 8	180	150	150	164	136	150	150
x 2, *x* 4, *x* 8	160	190	190	145	173	190	173
y 2, *y* 4	130	160	120	118	145	120	120
y 2, *y* 8	140	70	130	127	64	130	127
y 4, *y* 8	80	80	90	73	73	90	73
y 2, *y* 4, *y* 8	120	160	140	109	145	140	140
z 2, *z* 4	55	70	60	50	64	60	60
z 2, *z* 8	60	70	80	55	64	80	64
z 4, *z* 8	80	40	40	73	36	40	40
z 2, *z* 4, *z* 8	70	80	50	64	73	50	64

Participant 14							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	200	150	200	222	188	250	222
x 4, *y* 2, *z* 2	600	150	200	667	188	250	250
x 8, *y* 2, *z* 2	200	80	90	222	100	113	113
y 2, *z* 2	30	20	50	33	25	63	33
x 2, *y* 4, *z* 2	150	250	90	167	313	113	167
x 4, *y* 4, *z* 2	5	100	90	6	125	113	113

x 8, *y* 4, *z* 2	50	150	100	56	188	125	125
y 4, *z* 2	50	80	70	56	100	88	88
x 2, *y* 8, *z* 2	400	100	91	444	125	114	125
x 4, *y* 8, *z* 2	500	200	70	556	250	88	250
x 8, *y* 8, *z* 2	600	60	95	667	75	119	119
y 8, *z* 2	60	50	90	67	63	113	67
x 2, *z* 2	200	25	75	222	31	94	94
x 4, *z* 2	200	90	70	222	113	88	113
x 8, *z* 2	30	150	70	33	188	88	88
z 2	5	5	10	6	6	13	6
x 2, *y* 2, *z* 4	600	100	75	667	125	94	125
x 4, *y* 2, *z* 4	400	90	150	444	113	188	188
x 8, *y* 2, *z* 4	25	150	150	28	188	188	188
y 2, *z* 4	5	50	20	6	63	25	25
x 2, *y* 4, *z* 4	100	50	100	111	63	125	111
x 4, *y* 4, *z* 4	150	50	80	167	63	100	100
x 8, *y* 4, *z* 4	150	90	70	167	113	88	113
y 4, *z* 4	150	70	30	167	88	38	88
x 2, *y* 8, *z* 4	300	100	200	333	125	250	250
x 4, *y* 8, *z* 4	500	90	100	556	113	125	125
x 8, *y* 8, *z* 4	500	100	95	556	125	119	125
y 8, *z* 4	10	60	100	11	75	125	75
x 2, *z* 4	20	50	80	22	63	100	63
x 4, *z* 4	300	100	160	333	125	200	200
x 8, *z* 4	75	150	90	83	188	113	113
z 4	50	20	15	56	25	19	25

x 2, *y* 2, *z* 8	90	200	190	100	250	238	238
x 4, *y* 2, *z* 8	20	90	100	22	113	125	113
x 8, *y* 2, *z* 8	350	50	50	389	63	63	63
y 2, *z* 8	50	50	20	56	63	25	56
x 2, *y* 4, *z* 8	100	70	50	111	88	63	88
x 4, *y* 4, *z* 8	70	90	90	78	113	113	113
x 8, *y* 4, *z* 8	90	70	90	100	88	113	100
y 4, *z* 8	20	40	25	22	50	31	31
x 2, *y* 8, *z* 8	200	200	80	222	250	100	222
x 4, *y* 8, *z* 8	400	100	250	444	125	313	313
x 8, *y* 8, *z* 8	150	70	150	167	88	188	167
y 8, *z* 8	400	70	65	444	88	81	88
x 2, *z* 8	200	20	60	222	25	75	75
x 4, *z* 8	70	100	100	78	125	125	125
x 8, *z* 8	190	70	60	211	88	75	88
z 8	5	5	15	6	6	19	6
x 2, *y* 2	30	90	60	33	113	75	75
x 4, *y* 2	100	100	95	111	125	119	119
x 8, *y* 2	80	60	60	89	75	75	75
y 2	15	5	40	17	6	50	17
x 2, *y* 4	150	10	100	167	13	125	125
x 4, *y* 4	100	100	90	111	125	113	113
x 8, *y* 4	60	70	70	67	88	88	88
y 4	30	70	40	33	88	50	50
x 2, *y* 8	300	100	80	333	125	100	125
x 4, *y* 8	50	90	90	56	113	113	113

x 8, *y* 8	400	100	95	444	125	119	125
y 8	70	80	90	78	100	113	100
x 2	10	7	5	11	9	6	9
x 4	15	60	50	17	75	63	63
x 8	50	70	15	56	88	19	56
x 2, *x* 4	15	100	80	17	125	100	100
x 2, *x* 8	90	60	150	100	75	188	100
x 4, *x* 8	50	100	20	56	125	25	56
x 2, *x* 4, *x* 8	650	200	200	722	250	250	250
y 2, *y* 4	500	50	60	556	63	75	75
y 2, *y* 8	70	90	85	78	113	106	106
y 4, *y* 8	15	150	100	17	188	125	125
y 2, *y* 4, *y* 8	170	150	200	189	188	250	189
z 2, *z* 4	40	50	15	44	63	19	44
z 2, *z* 8	15	15	30	17	19	38	19
z 4, *z* 8	30	50	25	33	63	31	33
z 2, *z* 4, *z* 8	10	30	40	11	38	50	38

Participant 15							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	20	60	65	50	100	130	100
x 4, *y* 2, *z* 2	45	60	50	113	100	100	100
x 8, *y* 2, *z* 2	45	55	40	113	92	80	92
y 2, *z* 2	10	20	50	25	33	100	33
x 2, *y* 4, *z* 2	30	60	50	75	100	100	100

x 4, *y* 4, *z* 2	50	65	25	125	108	50	108
x 8, *y* 4, *z* 2	40	75	60	100	125	120	120
y 4, *z* 2	30	65	60	75	108	120	108
x 2, *y* 8, *z* 2	35	75	75	88	125	150	125
x 4, *y* 8, *z* 2	50	110	110	125	183	220	183
x 8, *y* 8, *z* 2	70	80	75	175	133	150	150
y 8, *z* 2	50	50	50	125	83	100	100
x 2, *z* 2	10	20	50	25	33	100	33
x 4, *z* 2	50	45	50	125	75	100	100
x 8, *z* 2	10	50	50	25	83	100	83
z 2	10	20	15	25	33	30	30
x 2, *y* 2, *z* 4	20	55	75	50	92	150	92
x 4, *y* 2, *z* 4	75	75	75	188	125	150	150
x 8, *y* 2, *z* 4	60	50	60	150	83	120	120
y 2, *z* 4	40	50	50	100	83	100	100
x 2, *y* 4, *z* 4	50	30	40	125	50	80	80
x 4, *y* 4, *z* 4	40	75	75	100	125	150	125
x 8, *y* 4, *z* 4	65	55	75	163	92	150	150
y 4, *z* 4	50	40	40	125	67	80	80
x 2, *y* 8, *z* 4	40	50	75	100	83	150	100
x 4, *y* 8, *z* 4	45	95	60	113	158	120	120
x 8, *y* 8, *z* 4	70	95	75	175	158	150	158
y 8, *z* 4	35	75	50	88	125	100	100
x 2, *z* 4	30	20	40	75	33	80	75
x 4, *z* 4	70	60	65	175	100	130	130
x 8, *z* 4	15	40	50	38	67	100	67

z 4	20	15	25	50	25	50	50
x 2, *y* 2, *z* 8	20	20	65	50	33	130	50
x 4, *y* 2, *z* 8	55	110	80	138	183	160	160
x 8, *y* 2, *z* 8	40	60	50	100	100	100	100
y 2, *z* 8	10	40	40	25	67	80	67
x 2, *y* 4, *z* 8	40	40	60	100	67	120	100
x 4, *y* 4, *z* 8	80	80	80	200	133	160	160
x 8, *y* 4, *z* 8	65	85	50	163	142	100	142
y 4, *z* 8	30	40	75	75	67	150	75
x 2, *y* 8, *z* 8	60	55	50	150	92	100	100
x 4, *y* 8, *z* 8	70	95	110	175	158	220	175
x 8, *y* 8, *z* 8	50	110	50	125	183	100	125
y 8, *z* 8	30	60	50	75	100	100	100
x 2, *z* 8	50	60	65	125	100	130	125
x 4, *z* 8	50	70	70	125	117	140	125
x 8, *z* 8	80	60	20	200	100	40	100
z 8	15	20	45	38	33	90	38
x 2, *y* 2	15	20	60	38	33	120	38
x 4, *y* 2	90	90	80	225	150	160	160
x 8, *y* 2	20	80	50	50	133	100	100
y 2	40	25	30	100	42	60	60
x 2, *y* 4	25	40	45	63	67	90	67
x 4, *y* 4	65	90	95	163	150	190	163
x 8, *y* 4	20	65	65	50	108	130	108
y 4	25	40	40	63	67	80	67
x 2, *y* 8	20	95	75	50	158	150	150

x 4, *y* 8	80	80	95	200	133	190	190
x 8, *y* 8	55	80	80	138	133	160	138
y 8	40	40	80	100	67	160	100
x 2	15	15	25	38	25	50	38
x 4	20	60	70	50	100	140	100
x 8	50	65	50	125	108	100	108
x 2, *x* 4	60	80	95	150	133	190	150
x 2, *x* 8	40	40	45	100	67	90	90
x 4, *x* 8	70	95	75	175	158	150	158
x 2, *x* 4, *x* 8	80	95	50	200	158	100	158
y 2, *y* 4	20	50	50	50	83	100	83
y 2, *y* 8	70	60	50	175	100	100	100
y 4, *y* 8	50	90	95	125	150	190	150
y 2, *y* 4, *y* 8	90	90	65	225	150	130	150
z 2, *z* 4	20	20	25	50	33	50	50
z 2, *z* 8	10	50	25	25	83	50	50
z 4, *z* 8	15	40	30	38	67	60	60
z 2, *z* 4, *z* 8	20	20	40	50	33	80	50

Participant 16							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	105	120	70	100	114	69	100
x 4, *y* 2, *z* 2	160	155	115	152	148	113	148
x 8, *y* 2, *z* 2	90	145	120	86	138	118	118
y 2, *z* 2	80	115	60	76	110	59	76

x 2, *y* 4, *z* 2	110	75	115	105	71	113	105
x 4, *y* 4, *z* 2	160	165	145	152	157	142	152
x 8, *y* 4, *z* 2	105	95	130	100	90	127	100
y 4, *z* 2	105	110	120	100	105	118	105
x 2, *y* 8, *z* 2	150	65	70	143	62	69	69
x 4, *y* 8, *z* 2	150	168	120	143	160	118	143
x 8, *y* 8, *z* 2	55	90	65	52	86	64	64
y 8, *z* 2	115	60	65	110	57	64	64
x 2, *z* 2	95	85	40	90	81	39	81
x 4, *z* 2	160	110	75	152	105	74	105
x 8, *z* 2	80	95	70	76	90	69	76
z 2	40	5	30	38	5	29	29
x 2, *y* 2, *z* 4	80	140	130	76	133	127	127
x 4, *y* 2, *z* 4	130	130	115	124	124	113	124
x 8, *y* 2, *z* 4	80	120	140	76	114	137	114
y 2, *z* 4	120	75	50	114	71	49	71
x 2, *y* 4, *z* 4	153	95	95	146	90	93	93
x 4, *y* 4, *z* 4	140	160	150	133	152	147	147
x 8, *y* 4, *z* 4	75	110	102	71	105	100	100
y 4, *z* 4	130	80	95	124	76	93	93
x 2, *y* 8, *z* 4	60	90	75	57	86	74	74
x 4, *y* 8, *z* 4	145	150	105	138	143	103	138
x 8, *y* 8, *z* 4	98	50	90	93	48	88	88
y 8, *z* 4	65	80	65	62	76	64	64
x 2, *z* 4	90	110	95	86	105	93	93
x 4, *z* 4	140	120	130	133	114	127	127

x 8, *z* 4	45	85	30	43	81	29	43
z 4	30	20	55	29	19	54	29
x 2, *y* 2, *z* 8	120	120	120	114	114	118	114
x 4, *y* 2, *z* 8	160	145	110	152	138	108	138
x 8, *y* 2, *z* 8	150	80	90	143	76	88	88
y 2, *z* 8	70	100	105	67	95	103	95
x 2, *y* 4, *z* 8	115	140	90	110	133	88	110
x 4, *y* 4, *z* 8	150	115	110	143	110	108	110
x 8, *y* 4, *z* 8	105	110	120	100	105	118	105
y 4, *z* 8	150	95	130	143	90	127	127
x 2, *y* 8, *z* 8	95	115	80	90	110	78	90
x 4, *y* 8, *z* 8	115	97	150	110	92	147	110
x 8, *y* 8, *z* 8	75	80	60	71	76	59	71
y 8, *z* 8	90	75	60	86	71	59	71
x 2, *z* 8	80	80	60	76	76	59	76
x 4, *z* 8	130	95	110	124	90	108	108
x 8, *z* 8	20	60	40	19	57	39	39
z 8	10	10	5	10	10	5	10
x 2, *y* 2	110	115	105	105	110	103	105
x 4, *y* 2	140	125	135	133	119	132	132
x 8, *y* 2	110	85	105	105	81	103	103
y 2	80	50	80	76	48	78	76
x 2, *y* 4	140	105	102	133	100	100	100
x 4, *y* 4	145	160	140	138	152	137	138
x 8, *y* 4	75	143	115	71	136	113	113
y 4	110	120	120	105	114	118	114

x 2, *y* 8	83	120	90	79	114	88	88
x 4, *y* 8	150	130	120	143	124	118	124
x 8, *y* 8	95	105	75	90	100	74	90
y 8	70	30	85	67	29	83	67
x 2	65	60	30	62	57	29	57
x 4	80	145	125	76	138	123	123
x 8	45	70	85	43	67	83	67
x 2, *x* 4	95	150	140	90	143	137	137
x 2, *x* 8	65	130	90	62	124	88	88
x 4, *x* 8	140	140	120	133	133	118	133
x 2, *x* 4, *x* 8	155	165	150	148	157	147	148
y 2, *y* 4	150	130	160	143	124	157	143
y 2, *y* 8	90	110	105	86	105	103	103
y 4, *y* 8	130	105	110	124	100	108	108
y 2, *y* 4, *y* 8	150	130	110	143	124	108	124
z 2, *z* 4	40	25	45	38	24	44	38
z 2, *z* 8	45	30	50	43	29	49	43
z 4, *z* 8	10	75	10	10	71	10	10
z 2, *z* 4, *z* 8	75	60	40	71	57	39	57

Participant 17							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	140	140	170	117	117	155	117
x 4, *y* 2, *z* 2	140	130	150	117	108	136	117
x 8, *y* 2, *z* 2	130	110	110	108	92	100	100

y 2, *z* 2	130	120	90	108	100	82	100
x 2, *y* 4, *z* 2	160	140	140	133	117	127	127
x 4, *y* 4, *z* 2	130	120	130	108	100	118	108
x 8, *y* 4, *z* 2	120	70	90	100	58	82	82
y 4, *z* 2	90	80	80	75	67	73	73
x 2, *y* 8, *z* 2	150	150	150	125	125	136	125
x 4, *y* 8, *z* 2	130	150	120	108	125	109	109
x 8, *y* 8, *z* 2	70	120	90	58	100	82	82
y 8, *z* 2	70	70	120	58	58	109	58
x 2, *z* 2	200	120	90	167	100	82	100
x 4, *z* 2	130	80	120	108	67	109	108
x 8, *z* 2	80	110	60	67	92	55	67
z 2	60	70	50	50	58	45	50
x 2, *y* 2, *z* 4	130	150	140	108	125	127	125
x 4, *y* 2, *z* 4	150	150	140	125	125	127	125
x 8, *y* 2, *z* 4	80	140	90	67	117	82	82
y 2, *z* 4	80	110	70	67	92	64	67
x 2, *y* 4, *z* 4	150	130	140	125	108	127	125
x 4, *y* 4, *z* 4	120	130	130	100	108	118	108
x 8, *y* 4, *z* 4	110	110	90	92	92	82	92
y 4, *z* 4	110	80	80	92	67	73	73
x 2, *y* 8, *z* 4	160	120	80	133	100	73	100
x 4, *y* 8, *z* 4	150	140	140	125	117	127	125
x 8, *y* 8, *z* 4	130	70	130	108	58	118	108
y 8, *z* 4	90	110	130	75	92	118	92
x 2, *z* 4	120	120	80	100	100	73	100

x 4, *z* 4	70	60	80	58	50	73	58
x 8, *z* 4	80	60	80	67	50	73	67
z 4	40	50	70	33	42	64	42
x 2, *y* 2, *z* 8	130	140	150	108	117	136	117
x 4, *y* 2, *z* 8	150	130	120	125	108	109	109
x 8, *y* 2, *z* 8	150	130	120	125	108	109	109
y 2, *z* 8	130	90	120	108	75	109	108
x 2, *y* 4, *z* 8	150	160	150	125	133	136	133
x 4, *y* 4, *z* 8	100	120	120	83	100	109	100
x 8, *y* 4, *z* 8	110	110	110	92	92	100	92
y 4, *z* 8	80	70	60	67	58	55	58
x 2, *y* 8, *z* 8	150	130	120	125	108	109	109
x 4, *y* 8, *z* 8	140	150	120	117	125	109	117
x 8, *y* 8, *z* 8	80	120	80	67	100	73	73
y 8, *z* 8	120	60	120	100	50	109	100
x 2, *z* 8	80	120	110	67	100	100	100
x 4, *z* 8	70	70	110	58	58	100	58
x 8, *z* 8	80	90	60	67	75	55	67
z 8	50	80	70	42	67	64	64
x 2, *y* 2	120	120	150	100	100	136	100
x 4, *y* 2	120	110	130	100	92	118	100
x 8, *y* 2	130	120	90	108	100	82	100
y 2	100	120	70	83	100	64	83
x 2, *y* 4	150	130	130	125	108	118	118
x 4, *y* 4	140	120	120	117	100	109	109
x 8, *y* 4	110	90	110	92	75	100	92

y 4	90	130	110	75	108	100	100
x 2, *y* 8	120	150	140	100	125	127	125
x 4, *y* 8	120	140	110	100	117	100	100
x 8, *y* 8	120	90	110	100	75	100	100
y 8	120	110	50	100	92	45	92
x 2	130	80	110	108	67	100	100
x 4	70	60	70	58	50	64	58
x 8	60	70	60	50	58	55	55
x 2, *x* 4	170	120	120	142	100	109	109
x 2, *x* 8	120	130	90	100	108	82	100
x 4, *x* 8	120	80	110	100	67	100	100
x 2, *x* 4, *x* 8	130	130	120	108	108	109	108
y 2, *y* 4	130	110	120	108	92	109	108
y 2, *y* 8	110	120	120	92	100	109	100
y 4, *y* 8	70	120	120	58	100	109	100
y 2, *y* 4, *y* 8	150	130	130	125	108	118	118
z 2, *z* 4	100	80	70	83	67	64	67
z 2, *z* 8	70	70	50	58	58	45	58
z 4, *z* 8	80	70	70	67	58	64	64
z 2, *z* 4, *z* 8	90	80	120	75	67	109	75

Participant 18							
Stimulus	Session 1	Session 2	Session 3	Session 1 normalised	Session 2 normalised	Session 3 normalised	Median
x 2, *y* 2, *z* 2	100	100	70	111	111	78	111
x 4, *y* 2, *z* 2	110	120	100	122	133	111	122

x 8, *y* 2, *z* 2	110	120	90	122	133	100	122
y 2, *z* 2	60	70	60	67	78	67	67
x 2, *y* 4, *z* 2	110	100	100	122	111	111	111
x 4, *y* 4, *z* 2	130	110	100	144	122	111	122
x 8, *y* 4, *z* 2	70	90	80	78	100	89	89
y 4, *z* 2	50	70	60	56	78	67	67
x 2, *y* 8, *z* 2	60	70	75	67	78	83	78
x 4, *y* 8, *z* 2	100	110	120	111	122	133	122
x 8, *y* 8, *z* 2	120	100	100	133	111	111	111
y 8, *z* 2	75	85	70	83	94	78	83
x 2, *z* 2	100	60	60	111	67	67	67
x 4, *z* 2	80	80	90	89	89	100	89
x 8, *z* 2	70	60	70	78	67	78	78
z 2	25	40	40	28	44	44	44
x 2, *y* 2, *z* 4	125	90	110	139	100	122	122
x 4, *y* 2, *z* 4	120	110	120	133	122	133	133
x 8, *y* 2, *z* 4	80	70	80	89	78	89	89
y 2, *z* 4	60	50	60	67	56	67	67
x 2, *y* 4, *z* 4	110	120	100	122	133	111	122
x 4, *y* 4, *z* 4	150	130	110	167	144	122	144
x 8, *y* 4, *z* 4	120	100	100	133	111	111	111
y 4, *z* 4	85	85	75	94	94	83	94
x 2, *y* 8, *z* 4	100	100	90	111	111	100	111
x 4, *y* 8, *z* 4	150	125	140	167	139	156	156
x 8, *y* 8, *z* 4	140	75	100	156	83	111	111
y 8, *z* 4	75	70	80	83	78	89	83

x 2, *z* 4	70	60	50	78	67	56	67
x 4, *z* 4	75	125	110	83	139	122	122
x 8, *z* 4	90	60	85	100	67	94	94
z 4	50	60	50	56	67	56	56
x 2, *y* 2, *z* 8	120	60	100	133	67	111	111
x 4, *y* 2, *z* 8	130	110	125	144	122	139	139
x 8, *y* 2, *z* 8	125	75	120	139	83	133	133
y 2, *z* 8	60	50	75	67	56	83	67
x 2, *y* 4, *z* 8	140	100	90	156	111	100	111
x 4, *y* 4, *z* 8	130	120	130	144	133	144	144
x 8, *y* 4, *z* 8	130	120	110	144	133	122	133
y 4, *z* 8	50	100	110	56	111	122	111
x 2, *y* 8, *z* 8	80	100	100	89	111	111	111
x 4, *y* 8, *z* 8	110	120	120	122	133	133	133
x 8, *y* 8, *z* 8	100	100	90	111	111	100	111
y 8, *z* 8	80	80	110	89	89	122	89
x 2, *z* 8	50	75	75	56	83	83	83
x 4, *z* 8	70	125	75	78	139	83	83
x 8, *z* 8	100	80	65	111	89	72	89
z 8	40	50	50	44	56	56	56
x 2, *y* 2	60	90	60	67	100	67	67
x 4, *y* 2	150	120	85	167	133	94	133
x 8, *y* 2	80	80	90	89	89	100	89
y 2	60	50	50	67	56	56	56
x 2, *y* 4	80	75	85	89	83	94	89
x 4, *y* 4	110	110	110	122	122	122	122

x 8, *y* 4	110	80	70	122	89	78	89
y 4	70	60	75	78	67	83	78
x 2, *y* 8	70	100	120	78	111	133	111
x 4, *y* 8	125	120	120	139	133	133	133
x 8, *y* 8	110	110	120	122	122	133	122
y 8	60	70	70	67	78	78	78
x 2	75	50	60	83	56	67	67
x 4	120	90	75	133	100	83	100
x 8	90	80	90	100	89	100	100
x 2, *x* 4	120	110	90	133	122	100	122
x 2, *x* 8	75	90	90	83	100	100	100
x 4, *x* 8	130	90	120	144	100	133	133
x 2, *x* 4, *x* 8	160	130	130	178	144	144	144
y 2, *y* 4	70	100	110	78	111	122	111
y 2, *y* 8	100	100	80	111	111	89	111
y 4, *y* 8	75	70	100	83	78	111	83
y 2, *y* 4, *y* 8	150	110	110	167	122	122	122
z 2, *z* 4	40	50	55	44	56	61	56
z 2, *z* 8	40	50	50	44	56	56	56
z 4, *z* 8	60	70	60	67	78	67	67
z 2, *z* 4, *z* 8	65	60	80	72	67	89	72

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