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UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

INSTITUTE OF SOUND AND VIBRATION RESEARCH

HUMAN RESPONSE TO COMBINED NOISE AND VIBRATION

by

Yu HUANG

Thesis for the degree of Doctor of Philosophy

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UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

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The discomfort caused by the noise and vibration in cars is investigated in this thesis to improve understanding of how subjective judgements of noise and vibration affect each other, how the relative discomfort of noise and vibration depend on their magnitudes and their durations, and how the total discomfort caused by simultaneous noise and vibration can be predicted.

Two experiments were designed to determine the magnitude-dependence of the relative discomfort caused by noise and vertical whole-body vibration. Subjects were presented with various combinations of different levels of noise and different magnitudes of vibration, and rated the discomfort caused by noise relative to the discomfort caused by vibration, and also vibration discomfort relative to noise discomfort. The subjective equivalence between noise and vibration was highly dependent on whether noise was judged relative to the vibration or vibration was judged relative to the noise. When judging noise, higher magnitude vibrations appeared to mask the discomfort caused by low levels of noise. When judging vibration, higher level noises appeared to mask the discomfort caused by low magnitudes of vibration.

The duration-dependence of the relative discomfort of noise and vibration was then investigated. Subjects were presented with 49 combinations of seven levels of noise and seven magnitudes of vertical whole-body vibration, and with five durations (2, 4, 8, 16, and 32 s). Either the discomfort caused by noise relative to the discomfort caused by vibration, or vibration discomfort relative to noise discomfort were rated in two sessions. The findings indicate that noise discomfort and vibration discomfort have a similar dependence on duration. The slopes expressing the levels of noise (sound pressure level or sound exposure level) judged equivalent to the levels of vibration (logarithms of the r.m.s. acceleration or vibration dose value) increased with increasing duration when judging noise relative to vibration, but were independent of duration when judging vibration relative to noise. As the durations increased from 2 to 32 s, the masking effect of vibration on noise discomfort decreased, whereas the masking effect of noise on vibration discomfort did not change.

Finally the noise discomfort in the presence of vibration, vibration discomfort in the presence noise, and the combined discomfort of simultaneous noise and vibration were investigated by employing the method of absolute magnitude estimation. Subjects judged noise discomfort, vibration discomfort, and their total discomfort in different sessions. The results suggest that, within the range of stimuli magnitudes investigated, the discomfort caused by vibration was reduced by noise whereas the judgement of noise discomfort was not significantly influenced by vibration. The total discomfort caused by simultaneous noise and vibration was well predicted by $\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}$, where ψ_v , ψ_s , and ψ_c , represent vibration discomfort, noise discomfort, and their total discomfort, respectively.

In conclusion, the relative discomfort caused by noise and vibration varies according to whether subjects are asked to judge noise discomfort relative to vibration discomfort or vibration discomfort relative to noise discomfort. There are masking effects of noise on the judgement of vibration discomfort, and of vibration on the judgement of noise discomfort, depending on the relative magnitudes of the two stimuli. The influence of vibration on the judgement of noise discomfort decreases with increasing duration of the stimuli, whereas the influence of noise on the judgement of vibration discomfort is independent of the duration. The discomfort caused by a combination of noise and vibration can be predicted by root-sums-of-squares of the discomfort caused by noise and the discomfort caused by vibration when these stimuli are presented alone.

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DECLARATION OF AUTHORSHIP

I, YU HUANG

declare that the thesis entitled

HUMAN RESPONSE TO COMBINED NOISE AND VIBRATION

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
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Signed:

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Definitions and abbreviations

ψ Subjective magnitude

ϕ Objective magnitude

k ‘Constant’ in Stevens’ power law

n ‘Exponent’ in Stevens’ power law

f Frequency

r.m.q. Root-mean-quad value: $\text{r.m.q.} = \left[\frac{\int_{t_1}^{t_2} x(t)^4 dt}{t_2 - t_1} \right]^{1/4}$

r.m.s. Root-mean-square value: $\text{r.m.s.} = \left[\frac{\int_{t_1}^{t_2} x(t)^2 dt}{t_2 - t_1} \right]^{1/2}$

r.s.q. Root-sums-of-quad value: $\text{r.s.q.} = \left(\sum x_i^4 \right)^{1/4}$

r.s.s. Root-sums-of-squares value: $\text{r.s.s.} = \left(\sum x_i^2 \right)^{1/2}$

SPL Sound pressure level: $L_{\text{Aeq}} (\text{dBA}) = 10 \log_{10} \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right)$

SEL Sound exposure level: $L_{\text{AE}} (\text{dBA}) = 10 \log_{10} \left(\frac{1}{t_0} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right)$

VDV Vibration dose value: $a_{\text{VDV}} = \left(\int_0^T a^4(t) dt \right)^{1/4}$

AME Absolute magnitude estimation

RME Relative magnitude estimation

Chapter 1 Introduction

1.1 General introduction

Noise and vibration hold an important position among the many factors that contribute to environments, such as the working environment, the living environment and the driving environment. Considering the acoustical environment, products that produce the same sound level in decibels (dB), e.g., sound pressure level (SPL) or loudness, can sound very different. The term 'sound quality' has been defined as the "adequacy of a sound in the context of a specific technical goal and/or task" based on such considerations (Blauert and Jekosch, 1997). The term 'compatibility' has also been used in this context, especially with regard to sounds accompanying the actions of users, e.g., the driver or passenger of a car. An analogous concept of quality, 'vibration quality', may also be appropriate for the evaluation and assessment of vibration. Specifically, the term 'responsiveness' has been used in this thesis with regard to sound and vibration accompanying the actions of driver of a car to shift gears.

In transport, comfort is one of the important factors in the study of sound/vibration quality of a vehicle, aircraft, or ship for both drivers and passengers. It is the most direct psychological correlate of ride quality in terms of the passenger's or the driver's subjective response. Hence it has become essential to discover the standards of comfort for noise and vibration in vehicles to satisfy the passenger and driver.

The comfort sensations of a driver might not be those for a passenger. Passengers may prefer an absolutely quiet family car with no vibration, whereas drivers may need a certain magnitude of sound and vibration to know the status of the vehicle ride. Some other psychological parameters, such as the 'responsiveness' may also be used to evaluate the response of a car to the driver's commands.

The comfort related to both sound and vibration in a car is influenced by both objective (physical) and subjective (psychological) parameters. Physical parameters such as the level of sound, e.g., SPL and sound exposure level (SEL), and the magnitude of vibration, e.g., the root-mean-square (rms) acceleration and vibration dose value (VDV) have already been well studied. However, apart from a desirable reduction of physical magnitudes, the magnitudes of psychophysical parameters, e.g., annoyance and discomfort also need to be considered.

Many studies have investigated human sensation of noise (e.g., annoyance) or human sensation of vibration (e.g., discomfort), and the standards and guidelines assume that noise and vibration affect humans separately. However it can be expected that people might feel a total discomfort from noise and vibration because of the combined effects of both, although neither of them exceeds a standardized limitation. In an environment where both sound and vibration exist, the sensations caused by sound and vibration might be influenced by each other, and the link between them can be expected to be complex. For instance, the annoyance of

noise might be reduced by the presence of the vibration on ride, and the discomfort of vibration might be reduced or increased by the presence of noise (Howarth and Griffin, 1990a, 1991; Miwa and Yonekawa, 1973; Quehl, 2001; Sandoover, 1970; Seidel *et al.*, 1989, 1990). The combined effects of noise and vibration on sensations of comfort might be a complex function of both sound and vibration, not simply the summation of the discomfort caused by the separate stimuli. Therefore, the current challenge is not only to design for sound or vibration separately, but to find the interactive effects of sound and vibration on the human response, and to understand the overall vibration-acoustic comfort.

1.2 Objectives

The main objective of this research is to improve understanding of the subjective response to combined noise and vibration and how this depends on the physical characteristics of the sound (e.g., SPL, frequency) and the vibration (e.g., acceleration, frequency, direction). The goal is to build a model for predicting or representing: (a) the equivalence between the 'discomfort' caused by typical noise and the 'discomfort' caused by typical vibration in cars; (b) the situations in which either noise or vibration will dominate adverse subjective reactions; (c) the mechanisms (e.g., synergistic, antagonistic) associated with the ways in which subjective responses to one stimulus (noise or vibration) are influenced by the other stimulus (vibration or noise), and (d) the interactive effects of combined noise and vibration on the evaluation of overall 'comfort' associated with a combination of noise and vibration. Besides comfort, the effects of noise and vibration on a vehicle's responsiveness perceived by a driver will also be considered, and the influence of other factors (e.g., using synchronized or random noise and vibration in laboratory), may also merit attention.

1.3 Organisation of the thesis

This thesis is divided into eleven chapters. Following this introduction chapter, a review of previous studies concerned with effects of combined noise and whole-body vibration on the human sensation of comfort is provided in Chapter 2. The apparatus employed in the field and in the laboratory and the statistical analysis methods are presented in Chapter 3. In Chapters 4 to 9, six experiments are reported: the effects of delays on responsiveness for driver and comfort for passenger cars are investigated in Chapter 4, the effects of sound level and vibration magnitude on the relative discomfort of noise and vibration are investigated in Chapter 5 and 6, the effects of duration on the relative discomfort of noise and vibration are investigated in Chapter 7, two magnitude estimation methods, the absolute magnitude estimation (AME) and the relative magnitude estimation (RME), are compared in Chapter 8, and the interaction and combined effects on the discomfort of simultaneous noise and vibration are investigated in Chapter 9. Chapter 10 contains a discussion of the whole study, and Chapter 11 concludes the thesis.

Chapter 2 Literature review

2.1 Introduction

This chapter reviews previous studies on the human response to noise and whole-body vibration, particularly on the annoyance and discomfort in vehicles and buildings. The review aims to identify areas in which there is insufficient knowledge or inconsistent findings, to provide a means of quantifying and predicting the relative and combined discomfort produced by noise and vibration in cars.

The literature review begins with the basis of psychoacoustics and human vibration, and then it is divided into three main sections, which are the relative effects of noise and whole-body vibration on the sensation of comfort, the interactive and combined effects of noise and whole-body vibration on the sensation of comfort, and conclusions.

2.2 Psychoacoustics and Human Vibration

Sound and vibration both result from the appropriate disturbance of elastic medium, but humans perceive sound by hearing while humans perceive vibration by touching. Noise can be defined as 'disagreeable or undesired sound' or other disturbance. Whole-body vibration occurs when the body is supported on a vibrating surface; whereas local vibration occurs when one or more limbs (or the head) are in contact with a vibrating surface. There are already a lot of reference books on acoustics and vibration (e.g., *Fundamentals of Acoustics* (Kinsler *et al.*, 2000), *Fundamentals of noise and vibration* (Fahy, F., and Walker, J., 1998), and *Handbook of Human Vibration* (Griffin, 1990)), and most definitions have been internationally standardised (e.g., ISO1996-1: 2003a, and BS6841: 1987). This section intends to make a brief summary of the basic principles in psychoacoustics and human vibration.

2.2.1 Introduction of psychoacoustics

Sounds are described by means of the time-varying sound pressure, $p(t)$, specified in Pascal (Pa). In psychoacoustics, values of pressure between 20 μPa (absolute threshold) and 100 Pa (threshold of pain) are relevant (Zwicker and Fastl, 1999). To deal with such an enormous range of sound pressures, the sound pressure level (SPL) is defined to be L_p dB greater or less than a reference sound pressure p_0 as

$$L_p = 10 \log_{10} \left(\frac{p}{p_0} \right)^2, \quad (2.1)$$

where p is the root-mean-square (r.m.s.) sound pressure in Pa, and $p_0 = 20 \mu\text{Pa}$ is the reference sound pressure (British Standards Institution, 2003a). Table 2.1 gives some examples of SPL in dB, corresponding to various environmental sounds.

Table 2.1 Typical sound levels in the environment (Howard and Angus, 1996).

Example sound	SPL (dB)	Description
Long range gunfire at gunner's ear	140	Ouch!
Threshold of pain	130	
Jet take-off at approximately 100m	120	
Peak levels on a night club dance floor	110	
Loud shout at 1m	100	Very noisy
Heavy truck at about 10m	90	
Heavy car at about 10m	80	
Car interior	70	Noisy
Normal conversation at 1m	60	
Office noise level	50	
Living room in quiet area	40	Quiet
Bedroom at night time	30	
Empty concert hall	20	
Gentle breeze through leaves	10	Just audible
Threshold of hearing for a child	0	

Sound level can also be quantified by the intensity. The sound intensity is the flow of energy (usually represented by the algebraic variable W) through a unit area (usually m^2) in a sound field, and is proportional to the square of sound pressure. Hence, the sound intensity level (SIL), L_I , in dB is defined as

$$L_I = 10 \log_{10} \left(\frac{I}{I_0} \right), \quad (2.2)$$

where I is the sound intensity of the sound field, and $I_0 = 1 \text{ pWm}^{-2}$ is the reference sound intensity (British Standards Institution, 1981). A 10-fold increase in pressure is equivalent to a 100-fold increase in intensity.

Frequency weighting networks have been developed to evaluate human exposure to noise over the audible range of human ears between approximately 20 Hz and 20 kHz, because human ears are not equally sensitive to sound at different frequencies. Figure 2.1 describes the attenuation provided by the A, B and C weighting networks. The A and C weighting networks are commonly used: A network modifies the frequency response to follow the equal loudness curve of 40 phon, and the C network approximately follows the equal loudness curve of 100 phon (e.g., British Standards Institution, 2003b). Though the C network better describes the industrial noise which contributes significantly to hearing damage, the A network is most widely used to describe the noise for habitability, community disturbance, and also the hearing damage. By employing the A network, the A-weighted equivalent continuous SPL, L_{Aeq} , is determined by:

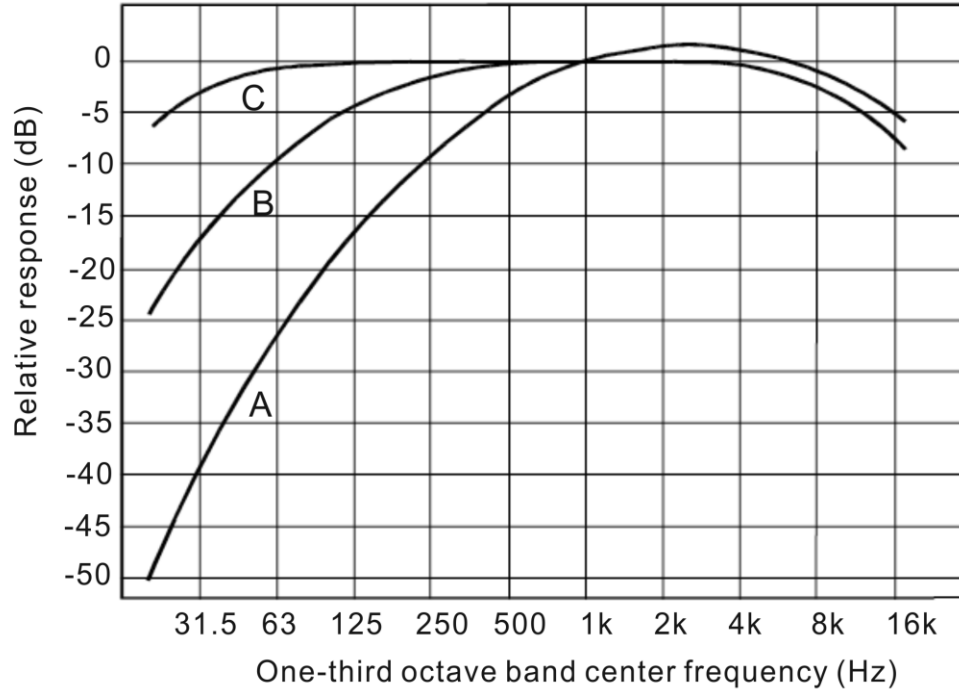


Figure 2.1 Frequency weighting characteristics for A, B and C networks (adapted from British Standards Institution, 2003b).

$$L_{Aeq} \text{ (dBA)} = 10 \log_{10} \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right), \quad (2.3)$$

where $p_A(t)$ is the instantaneous A-weighted sound pressure starting at time t_1 and ending at time t_2 , and p_0 is the reference sound pressure, 20 μPa (International Organization for Standardization, 2003a).

The sound exposure level, SEL, describes the energy of noise event having different time durations. The A-weighted sound exposure level, L_{AE} , of a discrete noise event is

$$L_{AE} \text{ (dBA)} = 10 \log_{10} \left(\frac{1}{t_0} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right), \quad (2.4)$$

where t_0 is the reference duration of 1 s (International Organization for Standardization, 2003a).

Loudness refers to the perception of SPL and SIL. The loudness of a pure 1000 Hz tone at 40 dB SPL is 1 sone, and the loudness level, L_N , of a pure 1000 Hz tone at 40 dB SPL equals to 40 phons (British Standards Institution, 1981). The standardized equal-loudness contours are presented in Figure 2.2, and each line is constructed so that all tones with the same loudness level are equally loud. The bottom line in Figure 2.2 represents the average threshold of hearing, or minimum audible field (MAF).

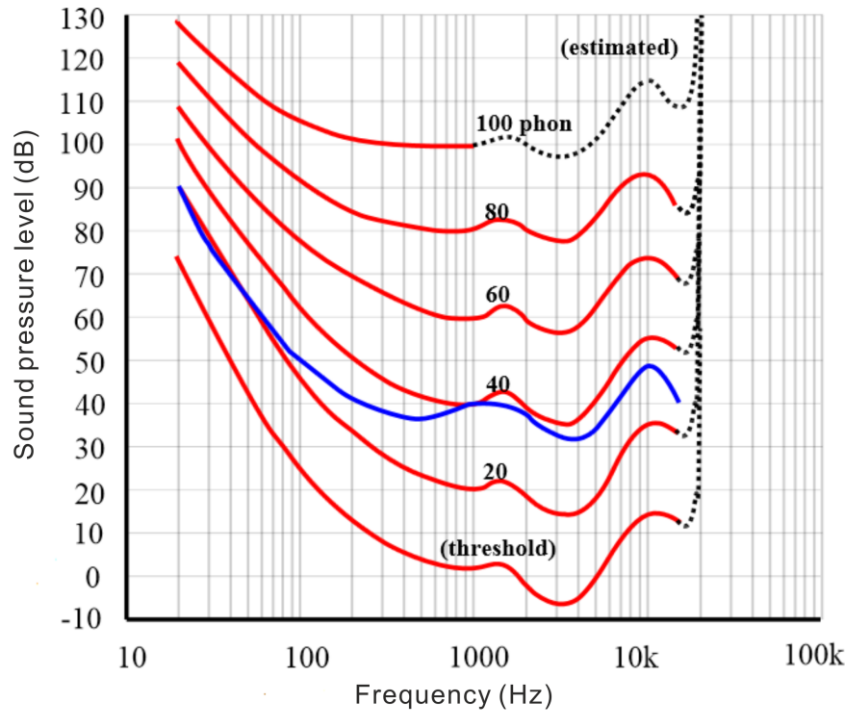


Figure 2.2 Equal-loudness contours (adapted from International Organization for Standardization, 2003b). Original ISO standard shown (blue) for 40-phon.

Four loudness models for complex sound have been developed as: (1) Stevens' loudness (Stevens, 1955, 1972), (2) Kryter's loudness (Kryter, 1985), (3) Zwicker's loudness (Zwicker and Scharf, 1965; Zwicker, 1999), and (4) Moore's loudness (Moore *et al.*, 1997; Moore, 1982, 2005; Glasberg and Moore 2006; Moore and Glasberg, 2007). Although there are some differences in the models, all of them consider the auditory system's properties of critical bands and the masking effects. Assume the frequency spectrum of a complex sound is divided into a number of frequency bands, the SPL in each band is determined and converted into loudness, then the contributions of the frequency bands are added together. Stevens' and Zwicker's loudness are standardized in ISO/DIS 532 B (International Organization for Standardization, 1975), and Moore's loudness is adopted by the American National Standards Institute for the calculation of the loudness of steady sound (Moore, 2005). Sharpness, tonality, fluctuation, and roughness are also widely used in psychoacoustics (Zwicker and Fastl, 1999).

Blauert and Jekosch (1997) proposed that the cognitive and affective process influencing the perception, interpretation, evaluation, and reaction to auditory stimuli need to be considered in addition to acoustic and psychoacoustic parameters. The cognitive process may be the perceptual process to identify a discrete event, and the affective process is related to the perception of a threatening or annoying event (Bradley and Lang, 2000).

Annoyance has been one of the first and most widely studied affective reactions to noise since antiquity to recent times (Berglund *et al.*, 1975; Griffin, 1975; Kryter, 2009; Guski, 1997; Guski *et al.*, 1999; Ouis, 2001; Schultz, 1978). It is a negative evaluation of noise from unwanted,

unacceptable, interfering or disturbing acoustic sources, and is highly associated with unpleasantness, nuisance or disturbance (Guski, 1997; Guski *et al.*, 1999).

Berglund *et al.* (1975, 1976) showed that noise ratings were highly related to loudness levels, although some noises were more annoying at low levels than at high levels. Annoyance appeared to correlate with the physical magnitude (e.g., SPL and SEL) for community and environmental noises, and with psychoacoustic parameters (e.g., loudness, sharpness, tonality, and roughness) for specific sources (Berglund *et al.*, 1975, 1976, 1981; Flindell, 1983, 1997; Guski, 1997; Kryter, 2009; Kuwano *et al.*, 1997; Schultz, 1978). Social surveys generally showed high levels of correlation between noise exposure and annoyance, (e.g., $r = 0.9$ for aircraft and approaching this for road traffic noise by Berglund *et al.* (1996)). However, Quehl (2001) stated that “noise annoyance reactions can be predicted only to some extent by acoustic and psychoacoustic properties; typically less than one third of the variation in individual annoyance reactions is accounted for by physical parameters.”

Non-auditory factors also influence noise annoyance and can be as important as the physical parameters (Field and Walker, 1982, 1983; Guski, 1999; Möhler, 1988). Two major classes of non-auditory factors may cause inter-individual and intra-individual qualitative and quantitative responses (Fields, 1993; Guski *et al.*, 1999; Schick, 1996): the personal variables including sensitivities, attitudes, and personality traits, among which the noise sensitivity contributes substantially to annoyance; the contextual variables including the living environment, activities, the individual's state and all the context of the sound stimuli.

Besides ‘annoyance’, various questionnaires based on the terms ‘bother’, ‘disturbance’, ‘dissatisfaction’, ‘noisiness’, etc., have been used in different noise comfort studies, and these comfort descriptors might have different meanings in different languages (Fahy and Walker, 1998; Guski *et al.*, 1999). The terms ‘comfort’ and ‘discomfort’ have been primarily used to denote affective evaluations and reactions to vehicle interior environments (e.g., Dempsey *et al.*, 1979a; Kim *et al.*, 2008; Suzuki, *et al.*, 2006). This thesis concerns the driver's and passenger's responses to vehicle interior noise, and uses ‘discomfort’ as the opposite of ‘comfort’ to describe the affective subjective reactions to the noise.

2.2.2 Introduction of human vibration

“Some motions can be a source of pleasure or satisfaction and so give a sense of well-being or comfort — but the study of the relation between vibration and comfort has mainly concerned the extent to which motions are responsible for displeasure, dissatisfaction and discomfort.” (Griffin, 1990, page 43). The discomfort produced by whole-body vibration depends mainly on the magnitude, frequency, direction, and duration of the vibration.

The magnitude of a vibration can be quantified by its displacement in m, its velocity in m/s^{-1} , or its acceleration in m/s^{-2} . For practical convenience, standards (e.g., British Standards Institution (1987) and International Organization for Standardization (1997)) advocate that the vibration intensity should be expressed in terms of the acceleration rather than the velocity or the

displacement, and be measured by accelerometers. The vibration magnitude should be calculated as an average value of the frequency-weighted acceleration (i.e., the r.m.s. acceleration), a_{rms} as:

$$a_{\text{rms}} = \left(\frac{1}{T} \int_0^T a^2(t) dt \right)^{\frac{1}{2}}, \quad (2.5)$$

where $a(t)$ is the frequency-weighted acceleration and T is the duration of the measurement period in seconds (British Standards Institution, 1987; International Organization for Standardization, 1997).

Analogous to the SPL, the acceleration level, L_a , in decibels is given by

$$L_a = 20 \log_{10}(a_{\text{rms}} / a_0), \quad (2.6)$$

where a_{rms} is the measured r.m.s. acceleration and $a_0 = 10^{-6} \text{ ms}^{-2}$ (International Organization for Standardization, 1983).

A logarithmic scale is commonly used in psychoacoustics due to the wide range of sound pressures and the logarithmic relation between sound pressure and the sensation of sound in human auditory system. However, with whole-body vibration there is merely a 1000:1 range between perception and pain thresholds, and vibration discomfort increases in almost linear proportion to the vibration magnitude: Figure 2.3 illustrates that the absolute threshold of perception of vertical whole-body vibration ranging from 12.5 to 80 Hz lies between approximately 0.01 and 0.05 ms^{-2} (Bellmann *et al.*, 2000); a magnitude of 0.1 ms^{-2} will be easily noticed, magnitudes around 1 ms^{-2} are usually considered to be uncomfortable, and magnitudes

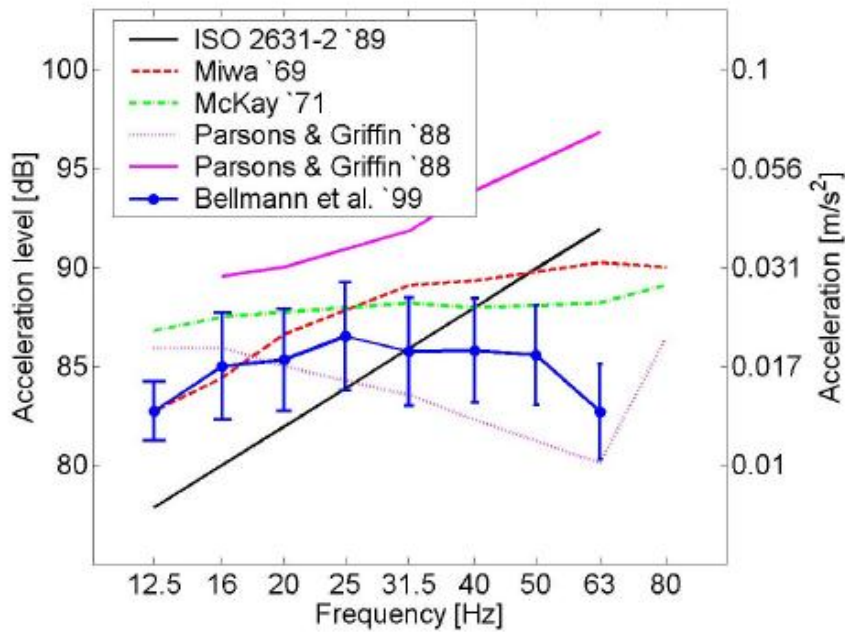


Figure 2.3 Perception thresholds of vertical whole-body vibration in dB or ms^{-2} (adapted from Bellmann *et al.*, 2000).

around 10 ms^{-2} are commonly dangerous (Griffin, 1990). Griffin (1990) also stated, “Decibels may give persons with a background in the measurement of sound an illusion of understanding the measurement of vibration magnitude. However, the expression of vibration magnitudes in terms of decibels adds a further and unnecessary unit which may impede a good fundamental understanding of the subject.” This thesis therefore uses the r.m.s. acceleration in ms^{-2} , not the acceleration level in dB, to describe the physical magnitude of vibration.

Human responses can be highly dependent on the frequency of vibration. The frequency range most often associated with effects of whole-body vibration on health, comfort, and perception is between 0.5 and 80 Hz (International Organization for Standardization, 1997). The degree to which vibration is transmitted to the body, and the effects caused by vibration in the body at any location depend on the vibration frequency. The influence of vibration frequency is now commonly accounted for by frequency weightings, which are the inverse of equivalent comfort contours for the comfort perception of vibration: where the contour is low the weighting is high (Griffin, 1990). The frequency-weighted value of a vibration is combined from all frequencies in proportion to their magnitude after frequency weighting.

Griffin (1998) compared the differences of the frequency weightings between BS 6841 (British Standards Institution, 1987) and ISO 2631 (International Organization for Standardization, 1997), and some conclusions are shown in Table 2.2 and Figure 2.4. It is assumed that frequency weightings for human response to vibration are dimensionless so that frequency-weighted acceleration has units of ms^{-2} (Griffin, 1990). The thesis uses frequency weightings W_d and W_c for for-and-aft whole-body vibration at the seat and the back, and W_b for vertical whole-body vibration at the seat for discomfort caused by whole-body vibration for seated persons (British Standards Institution, 1987).

Understanding of the effects of duration on human responses to vibration is far from complete. There is no conclusive evidence to support a universal time dependence of vibration effects on comfort: ISO 2631 (International Organization for Standardization, 1997) implies that the effects of whole-body vibration are independent of duration from 1 min to at least 4 min and then increase; however some studies have shown that subjective response to vibration appear to be dependent on the exposure duration, at least for short durations less than about 4 min (Griffin and Whitham, 1976, 1980; Hiramatsu and Griffin, 1984; Kjellberg and Wirkström, 1985; Kjellberg *et al.*, 1985).

Table 2.2 Frequency weightings for discomfort of whole-body vibration for seated persons.

Axis	BS 6841 (1987)	ISO 2631 (1997)
Seated persons:		
x-axis, seat surface	W_d	W_d
y-axis, seat surface	W_d	W_d
z-axis, seat surface	W_b	W_k
x-axis, seat-back	$0.8 \times W_c$	$0.8 \times W_c$

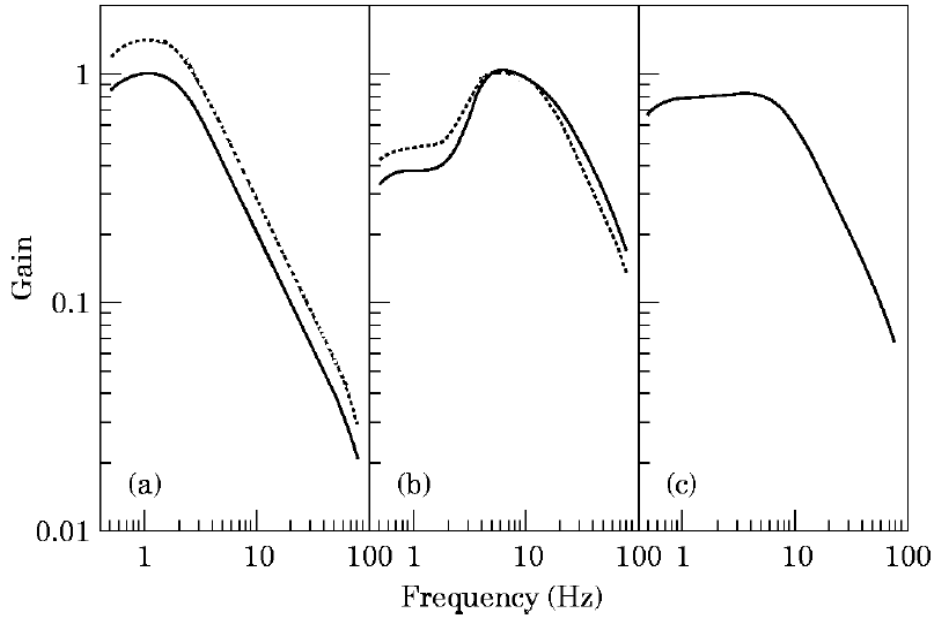


Figure 2.4 Comparison of the frequency weightings (with multiplying factors) used in the two standards for seated persons: (a) x- and y-axis seat vibration; (b) z-axis seat vibration; (c) x-axis backrest vibration. Key: —, BS 6841 (1987); ---, ISO 2631 (1997) (Griffin, 1998, permitted by the author).

The vibration dose value (VDV), a_{VDV} , of a vibration event is given in British Standards Institution (1987) and International Organization for Standardization (1997) by:

$$a_{VDV} = \left(\int_0^T a^4(t) dt \right)^{1/4}, \quad (2.7)$$

where $a(t)$ is the frequency-weighted acceleration and T is the duration of the measurement period in seconds. The VDV is the currently standardised expression for predicting how subjective impressions of vibration depend on the magnitude (r.m.s. acceleration), direction, frequency and duration of the stimuli. It doubles with a 16-fold increase in the duration of a vibration.

Besides the magnitude, direction, frequency, and duration of a motion, human responses to vibration are also influenced by intra-subject variability (changes in a person over time, e.g. posture, position, and orientation) and inter-subject variability (differences between people which reflect individual's biodynamic, physiological and psychological variables, e.g. body size and weight, body dynamics, age, gender, experience, and expectation) (Griffin, 1990).

2.3 The Relative Effects of Noise and Whole-body Vibration on the Sensation of Comfort

2.3.1 Introduction

Since 1970, a lot of investigations have been conducted to determine the physical correlates of human sensation of comfort (e.g., Bryan *et al.*, 1978; Fields, 1979; Griffin, 1975; Osborne, 1976, 1978; Osborne and Clarke, 1973, 1975; Richards *et al.*, 1978; Zepler *et al.*, 1973). Most of these studies concerned the comfort of passenger in vehicles and aircraft, and residents influenced by transportations. In general, these studies indicated that noise and vibration are among the most important factors which affect people in living and working environments and result in considerable annoyance, disturbance, and discomfort. Quantitative and qualitative measures of the sensation of comfort related to different intensities (e.g., SPL and r.m.s. acceleration) have been obtained by using 5- or 7- point scales, magnitude estimation, magnitude production, and paired comparison.

Stevens' power law (Stevens, 1986) was used in a wide range of subjective studies to determine the psychophysical relation between the subjective magnitude of a stimulus, ψ , (from magnitude estimate or rating) and its objective magnitude, ϕ , (e.g., SPL for sound, r.m.s. acceleration for vibration) by power function

$$\psi = k\phi^n, \quad (2.8)$$

where n is the rate of growth of the subjective sensation produced by the stimulus, and k is a constant.

In terms of logarithms, the power function becomes

$$\log_{10}(\psi) = n\log_{10}(\phi) + \log_{10}(k). \quad (2.9)$$

The equation describes a line in log-log coordinates with the slope n and the intercept $\log_{10}(k)$.

The following sections review studies conducted to determine the exponent n in the power function of noise and vibration, and the relative importance of noise and vibration on the sensation of comfort.

2.3.2 The effect of magnitude on subjective response to noise

According to Stevens' power law (Stevens, 1986), the subjective magnitude of sound (e.g., loudness, annoyance), ψ_s , is related to the physical magnitude of sound, ϕ_s by

$$\psi_s = k_s \phi_s^{n_s}. \quad (2.10)$$

Stevens proposed an exponent of 0.60 in the power function between the loudness and the intensity of 1000-Hz tones (Stevens, 1955). He suggested that for a constant spectrum and for all intensities greater than 50 dB, the loudness of continuous noises may be calculated from the equation:

$$\log_{10}(L) = 0.03N + S, \quad (2.11)$$

where S is the spectrum parameter which depends on the make-up of the spectrum including the phase relations.

In a series of subsequent experiments making cross-modality matches between loudness and ten other perceptual continua (60-Hz vibration on finger, length of line, brightness, etc.), Stevens (1966) obtained the values between 0.55 and 0.75 (except one of 0.99 determined by the hardness of squeezing rubber) with an average value of 0.64 for the exponent n_s . A slightly higher value of 0.676 was also reported by Stevens (1969) concerning a total of 68 experiments matching taste intensity of water from 46 pools and loudness.

The value of 0.6 for the exponent in the power function between loudness and SPL is consistent with results in a wide cross section of the literature (e.g., Hellman, 1976, 1981, 1982; Scharf and Fishken, 1970; Stevens, 1961, 1972, 1982), and has been standardized in ISO/R 131-1959 (E) (International Organization for Standardization, 1959). Many studies have indicated that loudness is the primary component of annoyance (Berglund *et al.*, 1976, 1981; Hellman, 1982; Powell, 1979), so the value of 0.6 is also widely quoted and has been recognized as the standard value for the growth rate of annoyance (discomfort). The relation between the noise annoyance (discomfort), ψ_s , and the SPL, L_{Aeq} , may be written as

$$\log_{10}(\psi_s) = 0.033L_{Aeq} + k, \quad (2.12)$$

where k is a constant that depends on the type of stimulus and the units used.

In a study of the subjective magnitude (loudness, annoyance, and noisiness) of noise-tone complexes ranging from 70 to 100 dB SPL, using the method of absolute magnitude estimation (AME), Hellman (1983) obtained exponents of 0.63 and 0.92 for loudness with a 1000-Hz tone and a 3000-Hz tone added to low-pass noise, respectively, and exponents of 0.95 and 1.1 for annoyance with a 1000-Hz tone and a 3000-Hz tone added to low-pass noise. Figure 2.5 shows the magnitude estimates of loudness and annoyance determined by a 1000-Hz tone (left) and a 3000-Hz tone (right) added to low-pass noise as a function of the overall SPL of the noise-tone complex. Hellman indicated that the exponents of loudness and annoyance depend on the characteristics of noise (i.e., the frequency of the tone, the spectrum of the noise, and the tone-to-noise ratio). The results also imply that the exponents of annoyance are greater than those of loudness.

Howarth and Griffin (1990a) investigated the annoyance caused by noise and vibration recorded simultaneously over 24 s in a building adjacent to a railway during the passage of a nearby train. The method of relative magnitude estimation (RME) was employed. When the annoyance caused by noise stimuli (20 to 5000 Hz, 54 to 79 dBA SEL) was judged relative to the reference (a combination stimulus of noise at 64 dBA SEL and vibration at $0.14 \text{ ms}^{-1.75}$ VDV), a value of 0.78 for the exponent, n_v , was obtained. The relation between the noise annoyance, ψ_s , and the SEL, L_{AE} , was determined as:

$$\log_{10}(\psi_s) = 0.039L_{AE} - 0.663. \quad (2.13)$$

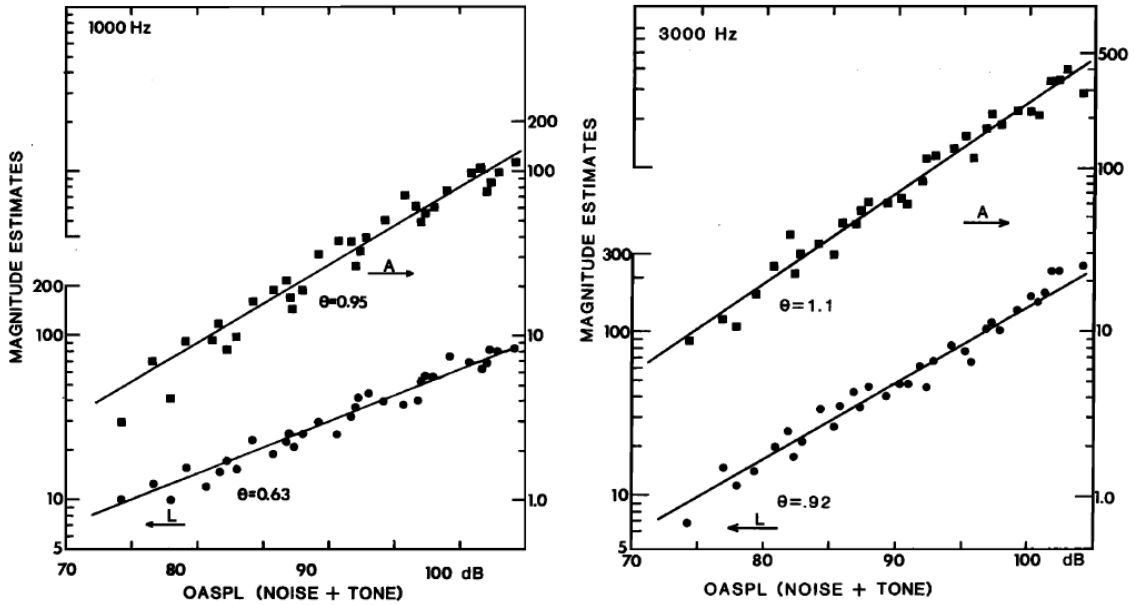


Figure 2.5 Magnitude estimates determined with a 1000-Hz tone (left) and a 3000-Hz tone (right) added to low-pass noise. Both loudness and annoyance are described by power functions. Each point indicates the geometric mean of 20 judgements by a group of ten listeners. Circles represent loudness judgements, squares represent annoyance judgements. Arrows refer to the numerical scale that corresponds to each attribute (adapted from Hellman, 1983).

Howarth and Griffin (1991) conducted a further study of the annoyance caused by simultaneous noise and vibration with various magnitudes, frequencies and durations of stimuli recorded in houses during the passage of six trains. Annoyance caused by broadband pink noise stimuli at 18 different levels (20-3000 Hz, 52.5-77.5 dBA SEL) was judged relative to the same reference employed in their previous study (Howarth and Griffin, 1990a), and an exponent of 0.72 was obtained. The relation between the noise annoyance, ψ_s , and the SEL, L_{AE} , was determined as:

$$\log_{10}(\psi_s) = 0.036L_{AE} - 0.512. \quad (2.14)$$

Howarth and Griffin stated that their exponents are in broad agreement with Stevens', although the exponents of 0.78 and 0.72 from annoyance judgements (Howarth and Griffin, 1990a, 1991) are greater than that of 0.6 from loudness judgements (Stevens, 1972).

Ward *et al.* (1996) employed three methods (category judgment, magnitude estimation, and cross-modality matching) to evaluate the loudness of two sets of 1000-Hz 1-s tones (a narrow-range set with stimuli from 55 to 82 dB in 3-dB steps; a wide-range set with 40, 43, 61, 64, 67, 70, 73, 76, 94, and 97 dB stimuli), and obtained exponents of 0.411 and 0.244 for the narrow-range and the wide-range conditions, respectively, when using '1-10' category judgment, 0.483 and 0.324 when using AME, and 1.017 and 0.759 when using cross-modality matching to the light intensities of a green-yellow LED. The values of the exponent n_s varied with the psychological methods employed, and the exponents obtained with AME, (i.e., 0.483 and 0.324),

differed from those using the same method in previous studies (e.g., Stevens, 1955; Hellman, 1976) which also investigated the loudness of 1000-Hz tones.

2.3.3 The effect of magnitude on subjective response to whole-body vertical vibration

According to Stevens' power law (Stevens, 1986), the subjective magnitude of vibration (e.g., annoyance, discomfort), ψ_v , is related to the physical magnitude of sound, ϕ_v by

$$\psi_v = k_v \phi_v^{n_v}. \quad (2.15)$$

Miwa (1968) investigated vertical whole-body vibration at 5, 20 and 60 Hz by using the corrected ratio technique (devised by Garner, 1954) and six magnitudes from 17 to 67 vibration greatness level (VGL, a logarithmic unit devised by Miwa) as reference stimuli. The exponent n_v was independent of frequency but dependent on the magnitude of the stimuli: 0.60 for magnitudes less than 1 ms^{-2} , and 0.46 for magnitudes greater than 1 ms^{-2} . However, as stated in other studies (e.g., Fothergill and Griffin, 1977; Howarth, 1989), the corrected ratio technique is very complicated and introduces many problems, so it has not been used in the later studies.

Shoenberger and Harris (1971) employed the method of relative magnitude estimation (RME) to investigate the subjective intensity of vertical whole-body vibration at seven frequencies (3.5, 5, 7, 9, 11, 15, 20 Hz). At each frequency, subjects compared seven magnitudes of test stimuli from 0.08 to 0.56 g (0.78 to 5.5 ms^{-2}) with a reference stimulus at 0.32 g (3.13 ms^{-2}), and the exponents between 0.86 and 1.04 were determined from the mean magnitude estimates, with

Table 2.3 Slopes of the regression lines between logarithm of mean magnitude estimates and logarithm of accelerations determined by Shoenberger and Harris (1971).

Frequency (Hz)	3.5	5	7	9	11	15	20
Slope	0.95	1.04	0.86	0.97	0.98	0.90	0.87

Table 2.4 Summary of linear regression analysis between logarithm of mean subjects' estimates and logarithm of acceleration ratio (Jones and Saunders, 1974).

Frequency (Hz)	Male			Female		
	Slope	Intercept	Correlation	Slope	Intercept	Correlation
5	0.88	0.14	0.64	0.95	0.10	0.82
8	0.94	0.09	0.63	0.95	0.13	0.73
10	0.96	0.07	0.74	0.93	0.09	0.83
16	0.94	0.11	0.09	0.93	0.11	0.81
20	0.93	0.11	0.66	0.90	0.15	0.78
30	0.91	0.11	0.71	0.92	0.10	0.85
40	0.90	0.13	0.66	0.99	0.11	0.79
80	0.90	0.14	0.78	0.94	0.22	0.76

the mean value of 0.94 averaged across all frequencies, as shown in Table 2.3.

Jones and Saunders (1974) investigated the subjective intensity of vertical whole-body sinusoidal vibration at frequencies between 5 and 80 Hz, with the acceleration magnitude between 0.05 to 0.20 peak g (0.35 to 1.4 ms^{-2}) at 5 Hz and between 0.3 to 1.7 peak g (2.1 to 11.8 ms^{-2}) at 80 Hz. Subjects were presented with two stimuli at the same frequency, to judge how many times more intense the second stimulus was than the first. Jones and Saunders summarised the average growth functions at each frequency for men and women separately, as shown in Table 2.3, and proposed an exponent of 0.93 for vertical sinusoidal whole-body vibration in the frequency range 5 to 80 Hz for sitting and standing men and women.

Clarke and Osborne (1975) investigated the subjective intensity of vertical whole-body vibration on standing men at 3, 5, 7, 20, 30, and 50 Hz with the approximate r.m.s. acceleration between 0.3 and 5.0 ms^{-2} . The exponents n_v obtained by the magnitude estimation, the magnitude production of fractionation (halving) and the multiplication (doubling) techniques are presented in Table 2.5. The mean exponent of 0.93 from magnitude estimation is less than the mean exponent of 1.17 from magnitude production. Clarke and Osborne suggested that magnitude estimation should be viewed with caution for the subjective judgements of vibration. Stevens (1986) indicated that due to the 'regression effect' (Stevens, 1971, 1986), the exponent of power function obtained by magnitude estimation averages slightly lower than the actual exponent, and that obtained by magnitude production averages slightly higher than the actual exponent. Therefore, when both magnitude estimation and magnitude production were carried out in a balanced design and two exponents were obtained, it seems sensible to use the geometric mean of the two exponents.

Leatherwood and Dempsey (1976) investigated discomfort caused by whole-body vertical sinusoidal vibration with ten frequencies between 2 and 29 Hz and nine magnitudes between 0.35 and 3.1 ms^{-2} r.m.s. Four psychophysical relationships between discomfort magnitude and the r.m.s. acceleration were compared at each frequency: $\psi = a\phi^b$, $\psi = a + b\log_{10}(\phi)$, $\psi = a10^{b\phi}$, and $\psi = a + b\phi$, where a and b are constants. Leatherwood and Dempsey (1976) selected a

Table 2.5 Power law exponents determined by Clarke and Osborne (1975a) using three methods.

Frequency (Hz)	Magnitude estimation	Magnitude production	
		Fractionation	Multiplication
3	1.08	1.24	1.51
5	1.08	0.99	1.46
7	0.94	0.98	1.28
20	0.90	0.79	1.12
30	0.78	0.78	1.54
50	0.82	0.96	-
Mean	0.93	0.96	1.38

linear law, $\psi = a + b\phi$, for its simplicity in practice, since no significant difference between correlations with the four relationships was found. However, the power relationship (i.e., $\psi = a\phi^b$), had larger correlation coefficients than the other three methods, with a mean exponent value of 1.24.

Fothergill and Griffin (1977) compared the methods of magnitude estimation and magnitude production in the subjective judgement of 10 Hz vertical whole-body vibration. In the magnitude estimation experiment, subjects were presented with a reference at 0.7 ms^{-2} r.m.s. and a test stimulus at one of the following magnitudes: 0.175, 0.23, 0.35, 0.7, 1.4, 2.1 and 2.8 ms^{-2} r.m.s. The two stimuli were alternated until subjects indicated the ratio of the 'strengths'. In the magnitude production experiment, subjects adjusted the test stimulus to the magnitude at which the strengths ratio of test and the fixed reference (0.7 ms^{-2} r.m.s.) was one of the following values: 1/4, 1/3, 1/2, 1, 2, 3 and 4. Table 2.6 shows the individual and mean values of the exponent n_v , with the correlation coefficients of the individual regression lines equal to or greater than 0.9. Two mean values of the exponent, 1.12 for magnitude estimation and 1.64 for magnitude production, were determined by calculating the regression through grouped data. These values are close to the average values of 1.13 and 1.75 from the mean values of individual exponents for magnitude estimation and magnitude production, respectively. Similar to the Clarke and Osborne (1975) study, the difference between the mean exponent obtained by the two methods might be caused by the 'regression effect' (Stevens, 1971, 1986). Fothergill

Table 2.6 Values of the exponent, n_v , obtained from individual subjects in the two experiments (Fothergill and Griffin, 1977).

Subject	Magnitude estimation	Magnitude production
1	1.22	2.08
2	1.07	1.20
3	0.91	1.75
4	0.94	1.43
5	1.39	1.48
6	1.37	2.12
7	1.18	1.47
8	1.02	1.97
9	1.20	1.47
10	1.14	2.80
11	1.13	1.36
12	1.05	3.20
13	0.82	0.93
14	1.32	1.41
Mean	1.13	1.75
Std. Dev.	0.18	0.62

and Griffin (1977) suggested unity for the exponent and stated that determination of an exact value is unnecessary because of a large individual variability in the values of exponent.

A cross-modality matching method with both noise and whole-body vibration was employed by Hempstock and Saunders (1976), who asked subjects to adjust the level of the dependent variable (noise or vibration) to be subjectively equivalent to a fixed independent sequential variable (vibration or noise). The 1/3 octave band random noise centred at 2000 Hz, and the sinusoidal vibration at 5, 10, 20, 30, 40, and 80 Hz were used. The noise and vibration stimuli were presented alternately in 2.5 second bursts with a 0.5 second interval between signals. When the discomfort caused by noise was the dependent variable, the vibration stimuli presented at 0.5, 1.0, 2.0, 4.0, and 6.0 ms^{-2} r.m.s. accelerations (except at 5 Hz where the acceleration was limited to 4.0 ms^{-2} r.m.s.) were used as the independent reference. When the discomfort caused by vibration was the dependent variable, the noise stimuli presented at 60, 70, 80, 90 and 100 dB SPL were used as the independent reference. By assuming an exponent of 0.6 for noise, the exponents for vibration were obtained at each frequency in Table 2.7. Hempstock and Saunders (1976) concluded that when the cross-modality method was employed, the value of the exponent would depend on which stimulus was the independent variable. The mean value of the exponent from the two procedures ranged from 0.85 to 0.99 at different frequencies, with the overall average exponent of 0.89. The average values were close to those reported in other studies (e.g., Jones and Saunders (1974) and Shoenberger and Harris (1971)).

Hiramatsu and Griffin (1984) conducted two experiments: the first experiment investigated the effects of duration and magnitude on the discomfort caused by whole-body vertical vibration at 8 Hz, and the second experiment investigated sixteen different 'non-steady' vibrations at 8 Hz over 30 s. In the first experiment, subjects were exposed to 25 vibration combinations of five magnitudes (for 2, 5, 10, 20, and 50 s) and five durations (for 0.5, 0.75, 1.11, 1.67, and 2.5 ms^{-2} r.m.s.) and gave magnitude estimates without any reference (i.e., the method of AME). The mean value of exponent in the power function between discomfort and acceleration magnitude was 0.964, with 95% confidence limits of 0.900 and 1.028. In the second experiment, an exponent of 1.203 was obtained. Hiramatsu and Griffin referred to Stevens (1975) to explain that a higher exponent was obtained in the second experiment because the range of stimuli employed was narrower.

Howarth and Griffin (1988) investigated the effect of frequency, magnitude and direction on the annoyance caused by vertical and horizontal whole-body vibration. The magnitude estimates of six acceleration magnitudes (0.04, 0.06, 0.1, 0.16, 0.25 and 0.4 ms^{-2} r.m.s. over 10-s duration) at nine frequencies (4 to 63 Hz at 1/2 octave intervals) relative to a noise reference (1/3 octave band centred at 1000 Hz, 70 dBA SPL over 5-s duration) were given by twenty subjects. Table 2.8 gives the mean values of the exponent at each frequency for vertical vibration, with a mean value of 1.21 averaged over all frequencies. Howarth and Griffin (1988) indicated that there were curves in the magnitude estimates on the log-log coordinates with greater exponents at

Table 2.7 The vibration growth function, n_v , as a function of frequency (Hempstock and Saunders, 1976).

Frequency (Hz)	n_v (vibration independent)	n_v (noise independent)
5	0.49 ± 0.07	1.43 ± 0.19
10	0.57 ± 0.07	1.11 ± 0.10
20	0.62 ± 0.07	1.36 ± 0.16
30	0.66 ± 0.06	1.30 ± 0.10
40	0.87 ± 0.07	1.20 ± 0.10
80	0.63 ± 0.06	1.43 ± 0.10

Table 2.8 Exponents for vertical vibration (Howarth and Griffin, 1988).

Frequency (Hz)	4	5.6	8	11.3	16	22.5	31.5	44.5	63	mean
Exponent, n_v	1.21	1.04	1.09	1.06	1.14	1.47	1.35	1.28	1.29	1.21

low magnitudes, whereas previous studies (e.g., Shoenberger and Harris, 1971; Clarke and Osborne, 1975; Hiramatsu and Griffin, 1984) found little evidence of such a curved relationship, possibly because they investigated substantially greater magnitudes than Howarth and Griffin (1988).

Howarth and Griffin (1990a) conducted an experiment to investigate the annoyance caused by noise and vibration in a building near a railway during the passage of trains (see also Section 2.3.2). The annoyance caused by six magnitudes of vibration stimuli (0.07, 0.10, 0.14, 0.20, 0.28 and $0.40 \text{ ms}^{-1.75}$ VDV, W_b weighting; frequency range 30 to 50 Hz) were judged relative to a reference stimulus (a combination stimulus of 64 dBA SEL and $0.14 \text{ ms}^{-1.75}$ VDV), and an exponent of 1.04 was obtained. The relation between the magnitude estimates of vibration annoyance, ψ_v , and the VDV, a_{VDV} , was determined in terms of logarithms as:

$$\log_{10}(\psi_v) = 1.04\log_{10}(a_{VDV}) + 2.39. \quad (2.16)$$

In a later experiment, Howarth and Griffin (1991) investigated the annoyance caused by eighteen magnitudes of vibration stimuli (10 to 60 Hz, 0.056 to $0.400 \text{ ms}^{-1.75}$ VDV). Employing the same method and the same reference as their previous experiment, they found an exponent of 1.18. The relation between the annoyance magnitude, ψ_v , and the VDV, a_{VDV} was determined in terms of logarithms as:

$$\log_{10}(\psi_v) = 1.18\log_{10}(a_{VDV}) + 2.57. \quad (2.17)$$

Morioka and Griffin (2006) investigated perception thresholds and discomfort for fore-and aft, lateral and vertical whole-body vibration. Subjects were exposed to whole-body sinusoidal vibration in each of the three axes at the 23 preferred 1/3 octave centre frequencies between 2

and 315 Hz and at the velocities from 0.02 to 1.25 ms⁻¹ r.m.s. in 3 dB steps. The method of RME (Stevens, 1986) was employed with the reference vibration at 20 Hz and 0.5 ms⁻² r.m.s. The exponents and constants for whole-body vertical sinusoidal vibration were obtained by using the power law with an additive constant:

$$\psi = k(\varphi - \varphi_0)^n, \quad (2.18)$$

where the additive constant, φ_0 , represents the threshold of perception. The median exponents, the constants, and the thresholds at each frequency are given in Table 2.9. The exponent depended on the vibration frequency: the greatest exponent was obtained around the principal resonance frequency of the body (4 Hz for the vertical axis), whereas the exponent trended to decrease between 16 and 100 Hz, and to increase between 125 and 315 Hz. The curvilinear relationship was apparent in the results of this study (see Figure 2.6 for example) and in the Howarth and Griffin (1988) study: when the data were plotted on log-log coordinates for

Table 2.9 Median exponents (n), constants (k) and thresholds (φ_0) for vertical axis (Morioka and Griffin, 2006).

Frequency (Hz)	Exponent (n)	Constant (k)	Threshold (φ_0)
2	0.626	185.91	0.014
2.5	0.697	185.10	0.016
3.15	0.751	192.13	0.018
4	0.897	227.98	0.018
5	0.669	212.76	0.015
6.3	0.687	215.97	0.015
8	0.702	215.48	0.019
10	0.624	193.55	0.022
12.5	0.814	203.19	0.022
16	0.827	181.80	0.025
20	0.776	149.93	0.025
25	0.757	136.11	0.028
31.5	0.697	136.52	0.030
40	0.600	127.67	0.027
50	0.489	110.59	0.025
63	0.462	102.78	0.025
80	0.424	93.11	0.026
100	0.413	85.98	0.025
125	0.448	78.76	0.032
160	0.379	85.31	0.027
200	0.464	64.80	0.033
250	0.515	52.99	0.044
315	0.535	45.47	0.065

subjective magnitude as a function of objective magnitude, a steeper slope (i.e., greater exponent of power function) was shown at low magnitudes. Morioka and Griffin (2006) obtained lower slopes by using curvilinear regression (Stevens' power law with an additive constant for the threshold) than by using linear regression (Stevens' power law without a constant representing the threshold). The authors indicated that Jones and Saunders (1974) found lower exponents than Howarth and Griffin (1988) probably because the subjective magnitudes determined by Howarth and Griffin fell into the lower section of the curve (where the slope is greater) while those determined by Jones and Saunders fell into the higher section of the curve (where the slope is reduced).

2.3.4 The relative effect of noise and whole-body vertical vibration on the sensation of comfort

Since noise and vibration usually influence human comfort in living and working environments, the relative importance of noise and vibration must be considered to understand the effect of the two modalities.

According to Stevens' power law (Stevens, 1986), if the subjective magnitudes of noise, ϕ_s , and vibration, ϕ_v , are judged to be equal, the subjective equivalence between noise and vibration can be expressed by

$$k_s \phi_s^{n_s} = k_v \phi_v^{n_v}. \quad (2.19)$$

It follows that the subjective equivalence between noise and vibration on log-log coordinates is given by either

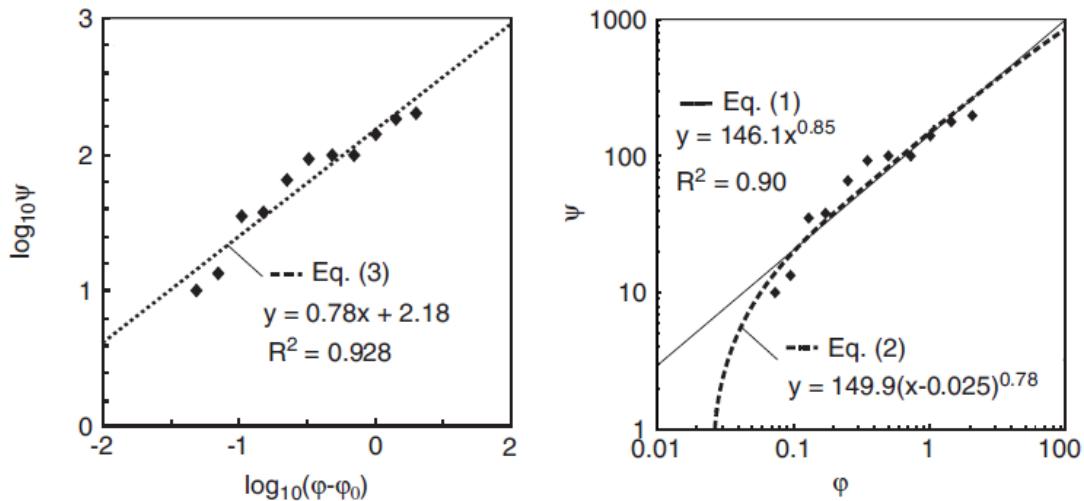


Figure 2.6 Responses to 20 Hz vertical vibration: linear regression (left), and sensation magnitude, ψ , as a function of vibration magnitude, ϕ (right). The additive constant, $\phi_0 = 0.025 \text{ ms}^{-2} \text{ r.m.s.}$ Eq. (1): $\psi = k\phi^n$, Eq. (2): $\psi = k(\phi - \phi_0)^n$ and Eq. (3): $\log_{10}(\psi) = n\log_{10}(\phi - \phi_0) + \log_{10}(k)$. (adapted from Morioka and Griffin, 2006).

$$\log_{10}(\varphi_s) = \log_{10}(k_v/k_s)^{1/n_s} + n_v/n_s \log_{10}(\varphi_v), \quad (2.20)$$

or

$$\log_{10}(\varphi_v) = \log_{10}(k_s/k_v)^{1/n_v} + n_s/n_v \log_{10}(\varphi_s). \quad (2.21)$$

If $L_{Aeq} \propto 20 \log_{10}(\varphi_s)$ (from Equation (2.3) assuming φ_s represents the A-weighted sound pressure) and $a_{rms} \propto \varphi_v$ (from Equation (2.5)), it follows from Equation (2.21) $\log_{10}(\varphi_v) = \log_{10}(k_s/k_v)^{1/n_v} + n_s/n_v \log_{10}(\varphi_s)$. (2.21) that the subjective equivalence between their r.m.s. values, L_{Aeq} , and a_{rms} is given by:

$$L_{Aeq} = k' + 20 \frac{n'_v}{n'_s} \log_{10}(a_{rms}), \quad (2.22)$$

where k' is a constant (dB). The relationship implies that when presented on a graph of $\log_{10}(a_{rms})$ versus L_{Aeq} , the subjective equivalence between noise and vibration should have a slope, s' , of $20(n'_v/n'_s)$ (dB).

The SEL, L_{AE} , and the VDV, a_{VDV} , are the currently standardized (e.g., BS6841: 1987; ISO1996-1: 2003a; ISO2631: 1997) expressions for predicting how subjective impressions of sound and vibration depend on the magnitudes (sound pressure or acceleration, respectively) and durations of the stimuli.

If $L_{AE} \propto 20 \log(\varphi_s)$ (from Equation (2.4)) and $a_{VDV} \propto \varphi_v$ (from Equation (2.7)), with noise and vibration of variable duration the subjective equivalence between the stimuli may be adequately described by their 'dose' values, L_{AE} and a_{VDV} , by:

$$L_{AE} = k + 20 \frac{n_v}{n_s} \log_{10}(a_{VDV}), \quad (2.23)$$

where k is a constant (dB). The relationship, which was proposed by Howarth and Griffin (1990b)

Table 2.10 The values of s and k in the relation $L_{AE} = k + s \log_{10}(a_{VDV})$, determined by further analysis of the results presented by Hempstock and Saunders (1973).

Vibration fixed stimulus			Noise fixed stimulus		
Frequency (Hz)	s	k (dB)	Frequency (Hz)	s	k (dB)
5	16.2	90.4	5	47.6	73.7
10	19.0	85.1	10	37.0	73.0
16	20.7	82.6	16	45.5	70.4
25	22.1	81.6	25	43.5	75.3
40	29.1	73.1	40	40.0	82.3
80	20.8	78.0	80	47.6	92.7

implies that when presented on a graph of $\log_{10}(a_{VDV})$ versus L_{AE} , the subjective equivalence between noise and vibration should have a slope, s , of $20(n_v/n_s)$ (dB)¹.

Hempstock and Saunders (1976) asked subjects to adjust the level of the dependent variable (noise or vibration) to be subjectively equivalent to a fixed independent sequential variable (vibration or noise). The 1/3 octave band random noise centred at 2000 Hz, and the sinusoidal whole-body vibration at 5, 10, 20, 30, 40, and 80 Hz were used (the direction of vibration was not reported, see also Section 2.3.3). When the discomfort caused by noise was the dependent variable, subjects altered the level of a noise stimulus to be subjective equivalent to a vibration stimulus at 0.5, 1.0, 2.0, 4.0, and 6.0 ms⁻² r.m.s. (except at 5 Hz where the acceleration was limited to 4.0 ms⁻² r.m.s.). When the discomfort caused by vibration was the dependent variable, subjects altered the magnitude of a vibration stimulus to be subjective equivalent to a noise stimulus at 60, 70, 80, 90 and 100 dB SPL. The equivalence between noise and vibration in terms of SPL and r.m.s. acceleration at each frequency were provided by the authors. Table 2.10 shows the values of slope, s , and intercept, k , in Equation (2.23) at each frequency determined by a further analysis on those data (see also Howarth, 1989). The results indicated that an increase in the vibration magnitude corresponded to a much smaller increase in the noise level with independent vibration than with independent noise. The average equivalence equation for the vibration independent session is given by:

$$L_{AE} = 81.8 + 21.3 \log_{10}(a_{VDV}). \quad (2.24)$$

The average equivalence equation for the noise independent session is given by:

$$L_{AE} = 77.9 + 43.5 \log_{10}(a_{VDV}). \quad (2.25)$$

Hempstock and Saunders (1976) concluded that the results obtained by the cross-modality method depended on which stimulus was the independent variable, but did not provide an explanation of the difference between the results from the two sessions. It might be explained by the 'regression effect': there may be a tendency for the subjects to shorten the range of whichever variable they are allowed to adjust (Stevens, 1959, 1986; Poulton, 1979). The equivalence between noise and vibration in terms of SEL and VDV may be obtained by averaging the results of the two sessions:

$$L_{AE} = 79.9 + 32.4 \log_{10}(a_{VDV}). \quad (2.26)$$

¹ Assume $\log_{10}(a_{rms}) = \log_{10}(a_{rms}/a_0)$, where $a_0 = 1 \text{ ms}^{-2}$, so $\log_{10}(a_{rms})$ is dimensionless. Analogously, $\log_{10}(a_{VDV})$ is dimensionless. Therefore, s' and s are dimensionless.

Fleming and Griffin (1975) investigated the relative importance of 1000 Hz pure tone noise and 10 Hz whole-body vertical vibration. Twenty seated subjects were exposed to all 64 combinations of eight levels of noises (65 dB to 100 dB SPL in 5 dB steps) and eight levels of

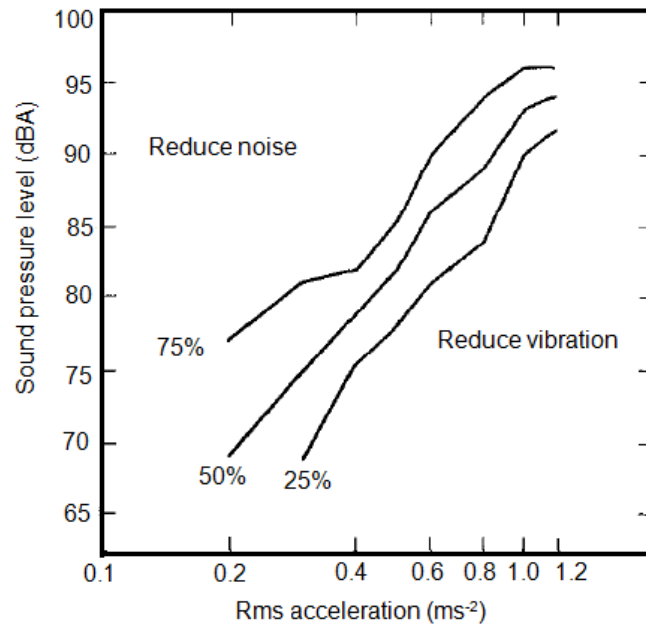


Figure 2.7 Percentage of the 20 subjects who indicated a preference for a reduction of the noise at the given vibration magnitudes and noise levels (adapted from Fleming and Griffin, 1975).

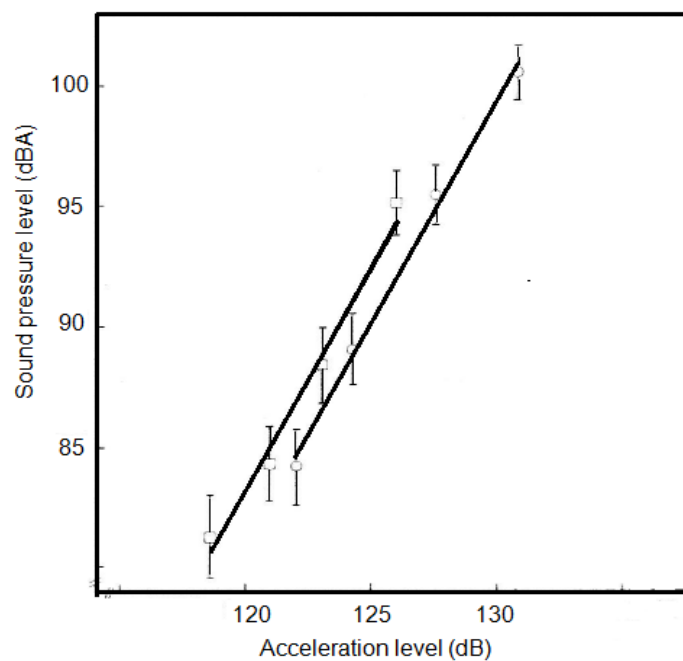


Figure 2.8 Mean SPLs at which the sound gave rise to the same degree of discomfort as the four intensities of the two vibrations ($\square$, 3.1 Hz; $\circ$, 6.3 Hz) (adapted from Kjellberg *et al.*, 1985).

vibration (0.20, 0.30, 0.40, 0.50, 0.60, 0.80, 1.00, and 1.20 ms⁻² r.m.s.). Both noise and vibration

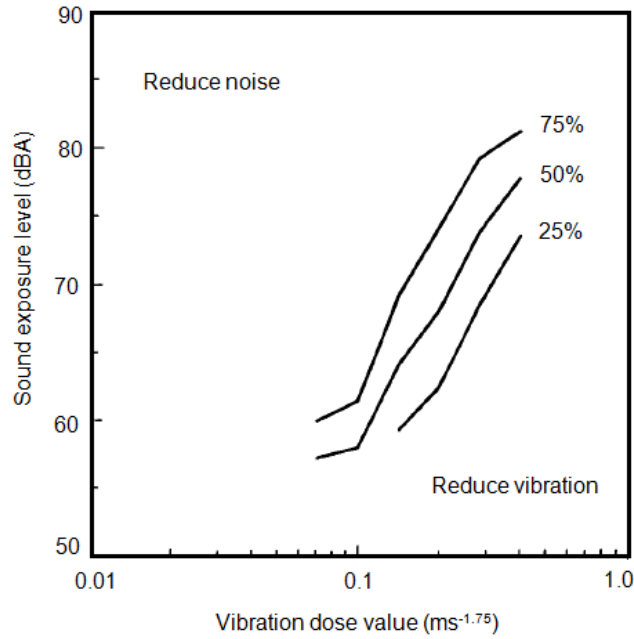


Figure 2.9 The 25th, 50th and 75th percentiles for the preference of reduction of noise (Howarth and Griffin, 1990b, permitted by the authors).

stimuli were presented simultaneously for 10 s. After each presentation the subjects were required to indicate which of the stimuli, noise or the vibration, they would prefer to be reduced. The percentage of subjects who prefer noise or vibration was shown in **Error! Reference source not found..** By choosing the value of 0.6 for the exponent of noise (i.e., n_s), Fleming and Griffin obtained the subjective equivalence between noise and vibration from a linear regression analysis of the 50th percentile:

$$0.03L_{Aeq} = 2.77 + 0.99\log_{10}(a_{rms}). \quad (2.27)$$

The relation may be expressed in terms of the SEL and VDV as

$$L_{AE} = 93.6 + 33.0\log_{10}(a_{VDV}). \quad (2.28)$$

In a study of the effect of vibration exposure duration on discomfort, Kjellberg *et al.* (1985) asked fifteen subjects to adjust broad-band noise (SPL between 15 and 115 dBA) to a level that gave the same discomfort as whole-body vertical vibration (0.95, 1.1, 1.4, and 2.0 ms⁻² r.m.s. at resonance frequency 3.1-Hz, and 1.3, 1.6, 2.4 and 3.5 ms⁻² r.m.s. at resonance frequency 6.3-Hz). The vibrations were recorded on the floor of a 12 ton forklift truck and a 1.5 ton forklift truck. The vibration stimuli were presented for 6 s and the noise stimuli were presented simultaneously with the vibration but continued for another 2 s after the termination of the vibration. The mean SPLs at which the sound had the discomfort as different acceleration levels of the 3.1 and 6.3 Hz vibration stimuli were shown in Figure 2.8. The subjective equivalence of

noise and vibration in terms of SEL and VDV was obtained a further analysis of the results (Howarth, 1989):

$$L_{AE} = 75.5 + 40.0 \log_{10}(a_{VDV}). \quad (2.29)$$

Howarth and Griffin (1990b) conducted an experiment to investigate the relative importance of the railway-induced noise vibration in a building. They employed the same method as Fleming and Griffin (1975) but with simulations of the noise and vibration recorded over 24 s in a building near a railway. With SELs from 59 to 84 dBA in 5-dB steps and VDV from 0.07 to 0.40 $\text{ms}^{-1.75}$ in 1.5-dB steps (W_b weighted), the percentage of subjects for the preference of reduction of noise was shown in Figure 2.9. The subjective equivalence between noise and vibration was obtained from linear regression on the 50th percentile data shown in Figure 2.9:

$$L_{AE} = 89.2 + 29.3 \log_{10}(a_{VDV}). \quad (2.30)$$

Paulsen and Kastka (1995) investigated the annoyance caused by reproductions of the noise and vibration of a tram and a hammermill. The noise and vibration produced by a decelerating tram were recorded on the first floor of a flat that was about 5-m away, and the noise and vibration produced by a working hammermill were recorded on the first floor of a two-storey building nearby. The duration of stimuli was limited to 16 s. With the r.m.s. velocity from 0.03 to 0.4 mm/s and the SPL from 28 to 61 dBA, the subjective equivalence equations between noise and vibration were determined in terms of SEL and r.m.s. velocity as

$$L_{AE} = 51.9 + 14.4 \log_{10}(v_m) \quad (2.31)$$

for tram stimuli, and

$$L_{AE} = 50.8 + 13.7 \log_{10}(v_m) \quad (2.32)$$

for hammermill stimuli.

Figure 2.10 contains the subjective equivalence contours between noise and vibration determined from the studies of Fleming and Griffin (1975), Hempstock and Saunders (1976), Kjellberg *et al.* (1985), Howarth and Griffin (1990b), and Paulsen and Kastka (1995). The equivalence between noise and vibration is illustrated for the range of VDV (of r.m.s. velocity for Paulsen and Kastka's contours) employed in the experiment.

The two contours of Hempstock and Saunders (1976) obtained from matching noise to fixed vibration stimuli and matching vibration to fixed noise stimuli differ much in equivalence between noise and vibration (i.e., the red line and the green line in Figure 2.10). Kjellberg *et al.* (1985) determined the equivalence by matching noise to fixed vibration stimuli. Surprisingly, their equivalence contour is consistent with what Hempstock and Saunders (1976) obtained by matching vibration to fixed noise stimuli. The slope of the equivalence contour of Kjellberg *et al.* (1985) is nearly twice that of Hempstock and Saunders (1976) with vibration as the fixed stimuli, and greater than those of other studies (e.g., Fleming and Griffin, 1975; Howarth and Griffin, 1990b; and Paulsen and Kastka, 1995).

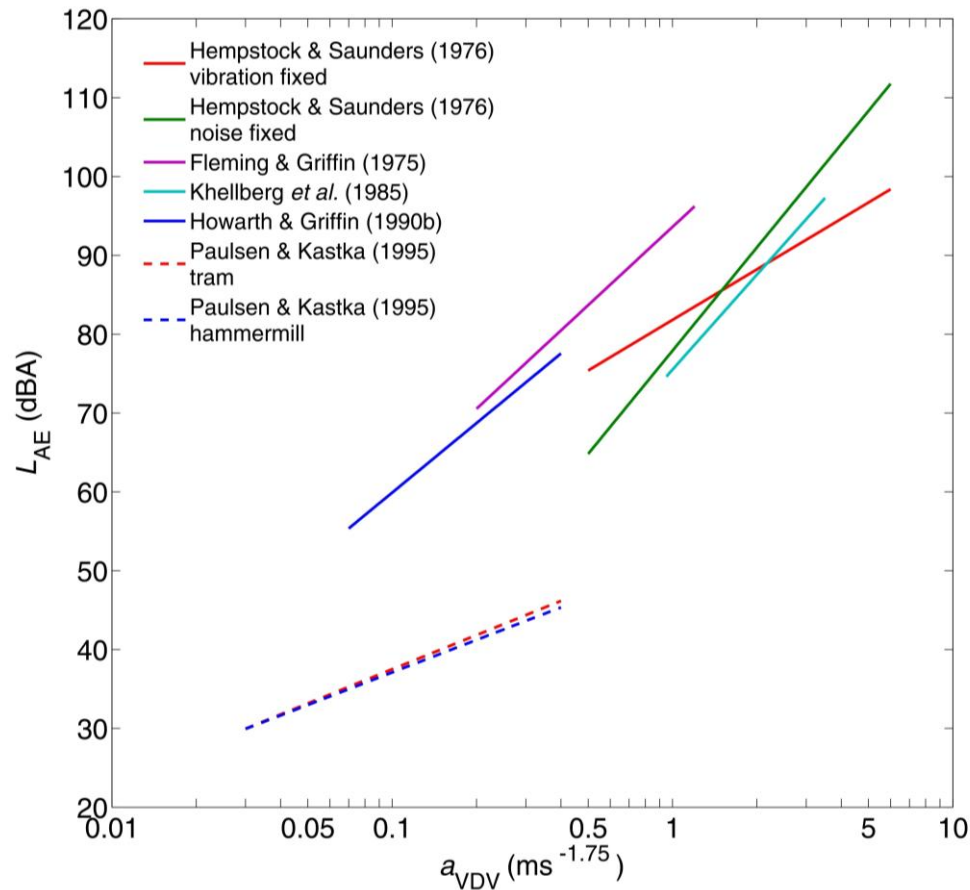


Figure 2.10 A comparison of the subjective equivalence contours from the previous studies.

The results of Howarth and Griffin (1990b) are most similar to those of Fleming and Griffin (1975) where the same method was employed, although Fleming and Griffin used sinusoidal sound and vibration and Howarth and Griffin used simulated vibration and noise in a building near the railway. The results obtained by Fleming and Griffin (1975) and Howarth and Griffin (1990b) suggest much higher noise levels equivalent to a vibration magnitude than Kjellberg *et al.* (1985) and Hempstock and Saunders (1976). The conflicting results might arise from the different methods and the different ranges of stimuli employed in the different studies.

The findings of Paulsen and Kastka (1995) correspond to a slope (for tram or hammermill) much less than found in other studies (e.g., Fleming and Griffin, 1975; Hempstock and Saunders, 1976; Howarth and Griffin, 1990b; and Kjellberg *et al.*, 1985). The divergence might be associated with the much lower levels of the sound stimuli employed in the Paulsen and Kastka (1995) study than in other studies.

2.4 The Interaction and Combined Effects of Noise and Whole-body Vibration on the Sensation of Comfort

Noise and vibration usually occur simultaneously in the environment and are perceived to be interdependent, yet many previous studies have mainly concerned the subjective response to noise and the subjective response to vibration separately. The standards, guidelines and protecting methods (e.g., British Standard Institute, 1987; International Standards Organisation, 2009) also recognize that noise and vibration affect human separately. However there have been a few studies concerned with the influence of one stimulus (noise or vibration) on the assessment of the other (vibration or noise), and with the total response to the two stimuli.

Guignard (1973) reviewed studies of interaction and combined effects of noise and vibration on subjective responses, sensory mechanisms, and performance. Another review of ride comfort studies in the United Kingdom by Griffin (1975) also reported some studies in subjective response to combined noise and vibration. Those early works showed that there were some interactive effects between noise and vibration, and the discomfort caused by a combination of noise and vibration might not equal to the summation of the discomfort of the stresses acting separately, but they did not give clear answers to the question. Howarth (1989) and Quehl (2001) have also reviewed some of the interaction and combined effects of noise and vibration discomfort in their doctoral dissertations. This section focuses on studies quantifying the subjective response to combined noise and whole-body vibration in a laboratory.

Jassen (1969) suggested a method of assessing the effect of simultaneous noise and vibration on ships by:

$$NVR = 10 \log_{10}(10^{0.1NR} + 10^{0.1VR}) \quad (2.33)$$

where NVR is the subjective assessment of simultaneous noise and vibration, NR is the subjective assessment of noise, and NV is the subjective assessment of vibration. This relation is based on the hypothesis that the subjective magnitudes of noise and vibration can be added in the way in which two SPL components are added. It is not applicable in the absence of noise or vibration: when $NR = 0$, $10^{0.1NR} = 1$; when $VR = 0$, $10^{0.1VR} = 1$. The experimental data were not reported by the author.

Sandover (1970) conducted a study to investigate the effect of vibration on equal loudness contours. Pure tone noise at frequencies between 125 Hz to 8000 Hz was matched with a 125 Hz reference tone and a 1000 Hz reference tone by four participants. The reference noise was presented without vibration, and the test noise was repeated with and without whole-body vertical vibration at 6 Hz 0.12 g (1.18 ms⁻²) r.m.s. and at 25 Hz 0.37 g (3.63 ms⁻²) r.m.s. The results of a comparison tone with and without 25 Hz sinusoidal vibration are shown in Figure 2.11. The noise settings were lower when a subject was exposed to 25 Hz vibration than when the subject was stationary, suggesting a masking effect of vibration on the sensation of noise. However, Sandover reported little effect of vibration for the other conditions.

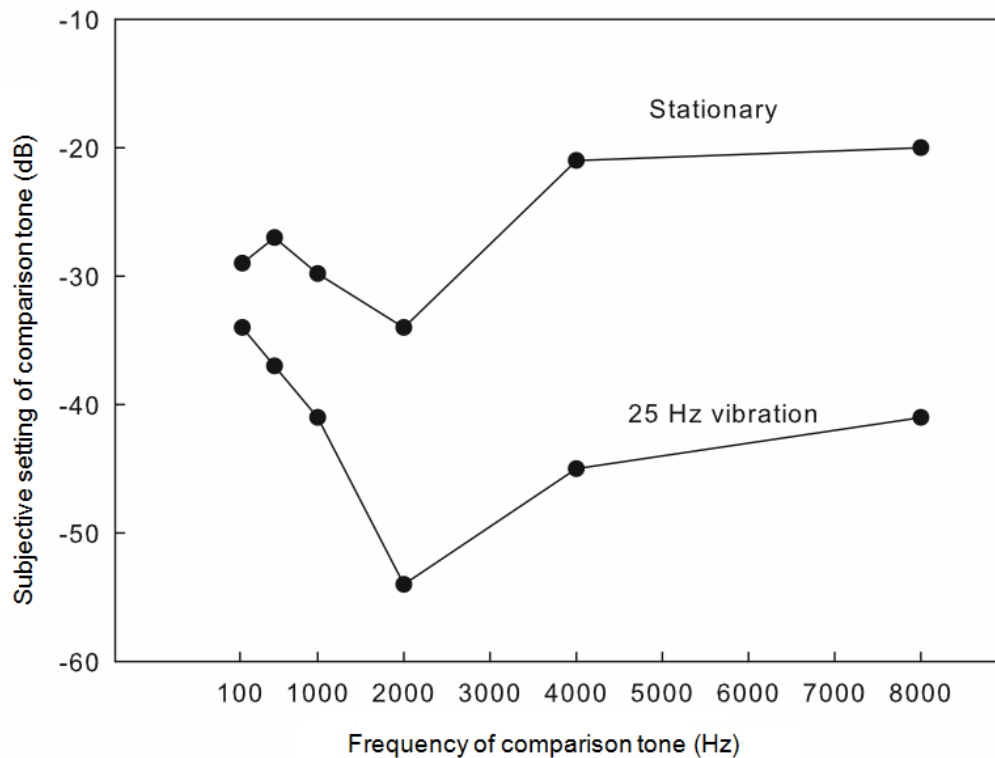


Figure 2.11 Equal loudness contours using 125-Hz reference tone, mean of four subjects (adapted from Sandover, 1970).

Innocent and Sandover (1972) investigated the effect of simultaneous noise and vibration on discomfort and task performance. Six combinations of two levels of white noise (80 and 90 dB) and three magnitudes of random vertical vibration (0.23, 0.63 and 1.14 ms⁻²) were employed as the stimuli. Thirteen subjects were presented with each of fifteen pairs of the combinations for 20 s and compared the relative discomfort of each combination. Then the subjects performed tracking and rating tasks during exposure to each combination for 10 min. After a tracking task performed during the last 2 min, the discomfort over each 10-min session was rated on an 11-point scale. Innocent and Sandover (1972) provided the following equation, which was obtained by the curve fitting method and applicable to the rating scale only:

$$\begin{aligned} R &= 0.230N + 38.846V - 16.538, \quad N \geq 72 \text{ dB} \\ R &= 38.846N, \quad N < 72 \text{ dB} \end{aligned} \quad (2.34)$$

where N is the noise level (dB), V is the r.m.s. acceleration magnitude (g r.m.s.), and R is the discomfort level relative zero (72 dB, 0 g r.m.s.). The authors concluded that “noise and vibration acting together give rise to a discomfort level which is equivalent to the summated discomfort levels of the stresses acting separately”.

Miwa and Yonekawa (1973b) investigated the interaction of noise and vibration. Impulsive vibration and noise of a diesel pile driver were recorded. The vibration had a repeated damped waveform with a repetition period of 1.5 s and with fundamental frequency at about 10 Hz. The

level of vibration was measured by a peak VL value (Miwa and Yonekawa, 1973a). Four experiments were carried out for vertical and fore-and-aft vibration. During the first experiment, ten subjects adjusted the magnitude of the pile driver vibration in the presence of four levels of noise (i.e., 70, 80, 90 and 100 dBA SPL) to match the sensation of the standard vibration (100 dBVL for vertical, and 96 dBVL for horizontal vibration) without the presence of noise. The results indicated a slightly larger matched vibration magnitude than the standard vibration magnitude. There was a trend for a masking effect of noise on the sensation of vibration. During the second experiment, ten subjects adjusted the pile driver vibration with 100 dBA noise to match five magnitudes of the standard vibration (80 to 100 dBVL in 5dB steps for vertical, and 76 to 96 dBVL in 5 dB steps for horizontal vibration) without noise. The results indicated good agreement between the variable vibration and fixed vibration. The masking effect of noise on the sensation of vibration was observed. During the third experiment, ten subjects adjusted the vibration without noise to match the standard vibration with 85 dBA noise added at different intervals: a) simultaneously, b) 0.5 s after the vibration, c) 0.5 s before the vibration, and b) 0.7 s before the vibration. The adjusted level was reduced by about 1.5 dB in condition a) and was reduced by about 2 dB in conditions b), c) and d). This suggests a masking effect of noise on the sensation of vibration, which is independent of the time interval between the noise and vibration. The fourth experiment matched the standard vibration to the sinusoidal vibration (5 Hz for vertical, and 2 Hz for horizontal vibration) when noise at 85 dBA was added at various time intervals. The results also indicated some masking effects of noise on the sensation of vibration.

Miwa and Yonekawa (1973b) concluded that the subjective magnitude of vibration was reduced by the presence of noise due to a masking effect when noise was present with the fixed vibration, whereas no such effect occurred when noise was present with the variable vibration. The masking effect was independent of the time interval between the noise and the fixed vibration. However, no statistical analysis was reported in this study.

NASA conducted a series of field and laboratory studies to investigate discomfort associated with combined noise and vibration (Dempsey *et al.*, 1976, 1979a; Hammond *et al.*, 1981; Kirby *et al.*, 1977; Leatherwood, 1979, 1984; Leatherwood and Dempsey, 1976; Leatherwood *et al.*, 1980, 1984, 1990; Stephens and Leatherwood, 1979; Stephens *et al.*, 1990). Some of these studies were reported below.

Dempsey *et al.* (1976) investigated the interaction and combined effects of noise discomfort and vibration discomfort. Four types of random vertical vibration (bandwidth of 5 Hz centred at frequencies of 3, 5, 7 and 9 Hz) at four magnitudes (0.03, 0.06, 0.09 and 0.12 g r.m.s.), and four types of random noise (octave band centred at frequencies of 250, 500, 5000 and 4000 Hz) at four levels (70, 75, 80 and 85 dBA SPL) were employed as the stimuli. All 256 combinations of noise and vibration stimuli were presented to 48 subjects along with 112 repeated stimuli. Subjects were asked to rate the noise only, to rate the vibration only, to rate both the noise and vibration separately, and to rate the discomfort caused by combined stimuli on a 9-point scale in separate parts of the experiment. The results indicated that vibration had no effect on the

assessment of noise discomfort; however, noise had a small but significant effect on the assessment of vibration discomfort. The results from assessment of noise only and vibration only in two parts were similar to the results from separate assessment in the same part. The authors concluded that subjects can separate the influence of noise and vibration, and the combined discomfort depends on both noise and vibration stimuli. However, the authors did not report which effect (e.g., additive or masking effect) the noise had on the vibration discomfort.

Dempsey *et al.* (1976, 1979a) continued to determine the interaction of noise discomfort and vibration discomfort, and to develop a quantitative method to predict the discomfort caused by simultaneous noise and vibration. The stimuli consisted of octave bands of noise centred at 500 and 2000 Hz and sinusoidal vertical vibration at 5 Hz or random vertical vibration with a 5 Hz bandwidth centred at 5 Hz. Four levels of noise at 65, 75, 85 and 95 dBA SPL were presented with six magnitudes of vibration at 0.02, 0.042, 0.064, 0.085, 0.106 and 0.130 g r.m.s. Forty-eight subjects participated in the study and rated the discomfort caused by the 15-s test stimuli relative to the 10-s reference stimuli (a combination of 65 dBA noise and 0.074 g 5-Hz vertical sinusoidal vibration). The results indicated that the discomfort caused by combined noise and vibration was not simply the sum of the individual effects of noise and vibration because of the interactions of vibration and noise. However, the authors then reported that the interactions of variables (e.g., the frequency and magnitude of noise and vibration) were not significant if a linear relationship was assumed between the vibration discomfort, ψ_v , and the r.m.s. acceleration, a_{rms} , and a power relationship was applied between noise discomfort, ψ_s , and the SPL, L_{Aeq} . The discomfort caused by combined noise and vibration was described as:

$$DISC = 0.337 + 32.1a_{rms} + 10^x, \quad (2.35)$$

where $x = -49.1a_{rms} - 3.16 + (0.0378 + 0.395a_{rms}) \times L_{Deq}$; $DISC$, the total discomfort caused by combined noise and vibration; a_{rms} , the overall root-mean-square acceleration in g; L_{Deq} , the D -weighted SPL in dBD.

The authors explained that the first two terms of Equation (2.35) represented the contribution of vibration to the total discomfort, and the third term represented the contribution of noise to the total discomfort, which was influenced by the magnitude of vibration. However, it is not clear why vibration acceleration appears in the third term, because neither the influence of noise on vibration was significant in a linear relationship between subjective magnitude and vibration magnitude, nor the influence of vibration on noise was significant in a power relationship between subjective magnitude and noise level.

Kirby *et al.* (1977) investigated the effects of simultaneously presented sinusoidal vertical vibration and broad-band noise centred at 500 Hz on ratings of ride quality. Two levels of noise (85 and 60 dBA SPL), three magnitudes of vertical vibration (0.05, 0.15, and 0.25 g peak), four frequencies of vertical vibration (2, 5, 9 and 15 Hz), and three replications of each possible stimulus were crossed by a $2 \times 3 \times 4 \times 3$ factorial design. Twelve seated women were exposed to the combinations of noise and vibration stimuli and rated the discomfort caused by each combination on a 9-point unipolar scale. There was a significant interaction among vibration

frequency, vibration magnitude, and noise level. The results indicated noise had a major effect on discomfort when presented with low magnitudes of vibration than with high magnitudes of vibration. Figure 2.12 indicated that the influence of noise diminished when the magnitude of vibration increased. However the author suggested that the reduction in the effect of noise might be due to the upper limit of the 9-point scale, and a magnitude estimation method would determine whether the results were affected by the limitations of the rating scale.

Leatherwood (1979) conducted a study to determine a numerical model of the discomfort produced by combined noise and vibration. A $4 \times 4 \times 4 \times 6$ factorial design was employed in the experiment, which consisted of four frequencies of vibration (3, 6, 9 and 12 Hz), four levels of vertical vibration discomfort (1, 2, 3, and 4 DISC), four levels of noise (76, 82, 88 and 94 dBA SPL), and six frequencies of noise (octave bands centred at 63, 125, 250, 500, 1000, and 2000 Hz). Leatherwood suggested using a 'vibration discomfort level' made the study focus on the incremental discomfort due to noise. Sixty subjects (49 women and 11 men) were instructed to give numerical values of the discomfort caused by combined noise and vibration relative to a reference vibration stimulus having a '100' discomfort.

The main effects and interactions of the four independent variables (i.e., frequencies of vibration, vibration discomfort level, noise level, and frequencies of noise) was tested by a four-factor analysis of variance and a post hoc multiple comparison procedure (Scheffé method). Leatherwood (1979) concluded that the use of 'vibration discomfort level' had effectively controlled the effect of vibration frequency on the discomfort because the result of a post hoc multiple comparison was not statistically significant ($p > 0.005$). However the analysis of variance indicated a significant effect of frequency ($p < 0.05$). Leatherwood explained that the

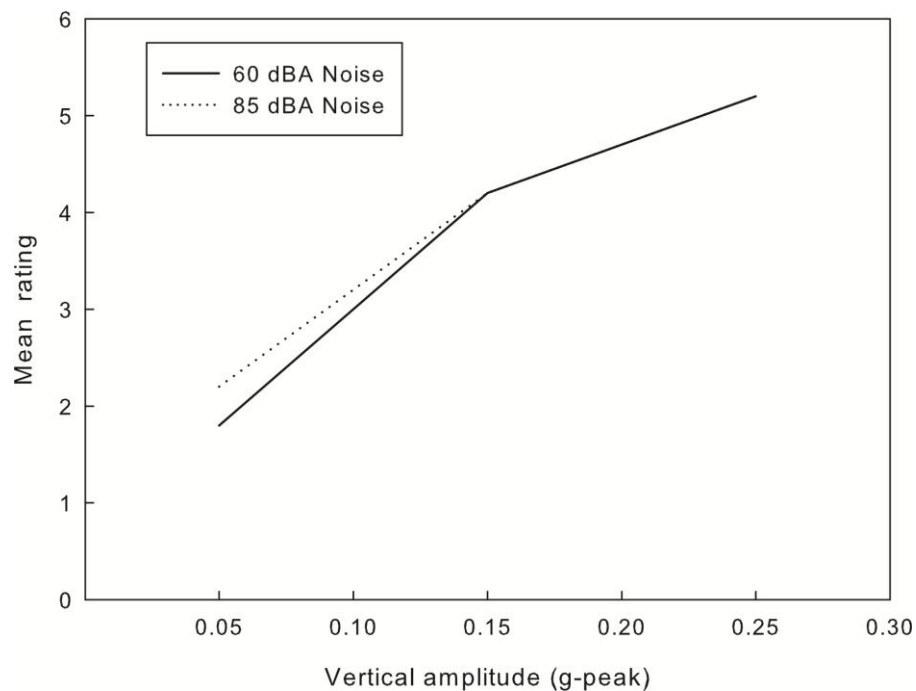


Figure 2.12 Mean subjective rating as a function of the interaction between magnitudes of vertical vibration and the levels of noise (adapted from Kirby *et al.*, 1977).

use of a repeated measures design did result in a more sensitive analysis in terms of finding statistical significance, so a more stringent level of significance for the post hoc tests was selected. Howarth (1989) suggested considering this explanation with some caution. Analysis of the results also indicated a significant effect of noise frequency on the discomfort, and this effect increased with the increasing noise level at the lowest and highest octave band (centred at 63 and 2000 Hz).

To determine the total discomfort produced by combined noise and vibration, first the discomfort of vibration alone was calculated by using the functions determined in previous studies (e.g., Dempsey *et al.*, 1979b), then the incremental discomfort due to noise was calculated by using the equation determined from the results of present study, finally total discomfort was obtained by the following equation:

$$D_I = D_{N+V} - D_V, \quad (2.36)$$

where D_{N+V} is the total discomfort caused by the combined noise and vibration, D_V is the discomfort caused by vibration alone, and D_I is the incremental discomfort due to the presence of noise. However, Howarth (1989) commented that the 'vibration discomfort level' was unlikely to have accounted for the effect of vibration frequency, and the frequency weightings associated with noise discomfort might not be correct.

In a further experiment Leatherwood *et al.* (1984) investigated the discomfort produced by reproductions of noise and vertical vibration from five types of helicopters. Subjects employed a 9-point scale to rate the discomfort caused by four levels of noise and three magnitudes of vibration for each type of helicopter. The results indicated that an increase in the magnitude of one stimulus (vibration acceleration or noise level) has less effect on the discomfort at high magnitude of the other stimulus (noise level or vibration acceleration) than at low magnitude. However, similar to the Kirby *et al.* (1977) experiment, the result may have been an artefact due to the upper limit of the 9-point scale.

The total discomfort of combined noise and vibration was predicted from the relation obtained by Leatherwood (1979). Figure 2.13 shows the mean discomfort rating as a function of the predicted discomfort. The correlation based on a second-order polynomial fit was high ($r = 0.914$), and the authors justified the second order polynomial as considering the limit of the 9-point scale. However, the necessity of the second order predicting equation seemed in doubt.

Seidel *et al.* (1989) investigated the effects of vibration frequencies and noise levels on the subjective intensity of sinusoidal whole-body vibration. Nine subjects were exposed to sixteen combinations of two levels of noise (65 and 86 dBA SPL) and eight vibration stimuli resulting from four frequencies (0.63, 1.25, 2.5 and 5 Hz) and two magnitudes (1 and 2 ms⁻² r.m.s.). The frequency of noise was described as an average over data from field-measurements of different types of excavators, industrial tractors, and heavy trucks. The intensity of vibration was matched with three different modalities, the handgrip force, length of a line and brightness of a milk-glass. The duration of each exposure condition was 210 s. Analysis of results (ANOVA) indicated a

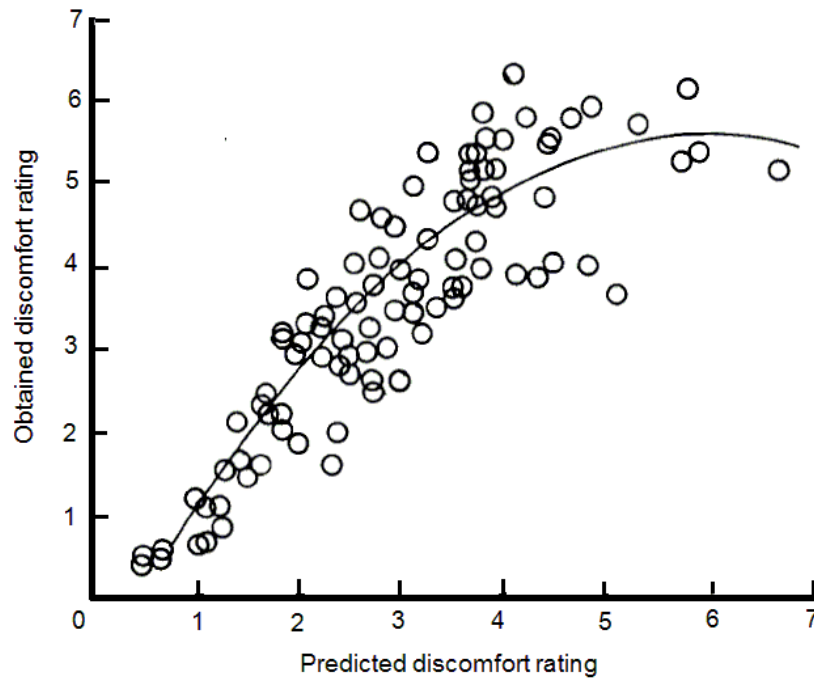


Figure 2.13 Relationship between obtained mean discomfort ratings and predicted discomfort ratings (adapted from Leatherwood *et al.*, 1984)

greater estimate of the vibration intensity in the presence of high level of noise, and a tendency for the effect of noise on judgements of vibration intensity to increase when the subjective intensity of vibration decreased. The synergistic effects of noise, however, were not systematic at different vibration frequencies and intensities.

Seidel *et al.* (1990) conducted a further study of the subjective intensity, annoyance and performance associated with simultaneous noise and whole-body vibration. Twelve male drivers experienced twelve combinations of three magnitudes of 3-Hz vibration (0.55, 1.1 and 2.2 ms⁻² r.m.s.) and four levels of low-frequency broadband noise (65, 79, 82 and 85 dBA SPL). The methods of AME and cross-modality matching with the length of a line were employed to determine: 1) annoyance caused by noise and whole-body vibration, 2) intensity of vibration, 3) intensity of noise, and 4) difficulty to perform the job as a driver. Each combination lasted for about 300s: subjects adapted to each combination for 60 s and then made judgements during the continuing exposure. The results indicated that noise had a synergistic effect on the evaluation of vibration intensity, but vibration had no effect on the evaluation of noise intensity. The annoyance was significantly affected by noise intensity, vibration intensity and their interactions. A multiple regression equation based on the results of cross-modality matching was provided to predict the annoyance due to simultaneous noise and vibration taking into consideration their interaction:

$$\log_{10}(LL) = -13.3987 - 0.0133 \times VL \times NL + 0.1203 \times VL + 0.1932 \times NL \quad (2.37)$$

where LL = length of a line in mm, VL = vibration level in dB with $0 \text{ dB} = 1 \mu\text{ms}^{-2}$, NL = noise level in dBA. A multiple regression of the results of AME was not employed by the authors because there was more significant individual variability with AME than with cross-modality.

Seidel *et al.* (1990) also reported the exponents in the power functions of vibration intensity and noise intensity (i.e., n_v and n_s): 0.73 with AME and 0.85 with cross-modality match for n_v , and 0.62 with AME and 0.69 with cross-modality match for n_s . The authors suggested the greater exponents with cross-modality matching than with AME were caused by the relatively small range of the target 'length of line' – a 'range effect' (Poulton, 1968, 1979; Stevens, 1986).

Howarth and Griffin (1990a) conducted a laboratory experiment to investigate both the interaction and the combined effects of railway-induced noise and vibration in buildings (see also Sections 2.3.2 and 2.3.3). The method of RME was employed and 36 combinations of six levels of noise (54, 59, 64, 69, 74 and 79 dBA SEL) and six magnitudes of vibration (0.07, 0.10, 0.14, 0.20, 0.28 and $0.40 \text{ ms}^{-1.75}$ VDV) were used as stimuli. Twenty-four subjects attended three sessions of the experiment: a) for session A, 36 combination stimuli and six vibration stimuli were presented and the vibration annoyance was rated, b) for session B, 36 combination stimuli and six noise stimuli were presented and the noise annoyance was rated, c) for session C, six vibration stimuli, six noise stimuli and their combinations were presented and the annoyance caused by the combined noise and vibration was rated. The authors suggested that vibration didn't influence the judgement of noise annoyance, whereas with high magnitudes of vibration the vibration annoyance was increased by a high level of noise, but with low magnitude of vibration the vibration annoyance was reduced by high levels of noise.

By multiple regression analysis, two equations predicting the total annoyance produced by combined noise and vibration were obtained with and without including their interactions, respectively:

$$\psi = 15.9 + 260\phi_v^{1.04} + 0.167\phi_s^{0.039}, \quad (2.38)$$

$$\psi = 10.8 + 290\phi_v^{1.04} + 0.178\phi_s^{0.039} - 0.066\phi_s^{0.039}\phi_v^{1.04}, \quad (2.39)$$

where ψ is the total annoyance, $\log_{10}(\phi_s)$ is the SEL in dBA and ϕ_v is the VDV in $\text{ms}^{-1.75}$. The interaction variable, $0.066\phi_s^{0.039}\phi_v^{1.04}$, contributed very little to the predicted subjective magnitude ψ , and the correlation coefficients between the independent variable, ψ , and the dependent variables, ϕ_s and ϕ_v , of Equations (2.38) and (2.39) were the same ($r = 0.97$, $p < 0.005$). Howarth and Griffin (1990a) suggested the addition of the interaction variable did not improve agreement between measured and predicted annoyance, and the total annoyance might not be simply predicted by adding the term of form $\phi_s^x \phi_v^y$ because the interactions of noise and vibration might be complex.

Howarth and Griffin (1991) conducted a further study on the annoyance caused by simultaneous noise and vibration (see also Sections 2.3.2 and 2.3.3). Twenty subjects were exposed to 90 combinations (fifteen combinations for each of the six trains) of noise and vibration recorded in buildings near railway with durations varying from 7 to 20 s. The same method and reference stimulus as their previous study (Howarth and Griffin, 1990a) were employed, and the predicting equation for the total annoyance was given by:

$$\psi = 22.7 + 243\varphi_v^{1.18} + 0.265\varphi_s^{0.036}, \quad (2.40)$$

where ψ is the total annoyance, $\log_{10}(\varphi_s)$ is the SEL in dBA and φ_v is the VDV in $\text{ms}^{-1.75}$. The correlation coefficient between independent variable, ψ , and the dependent variables, φ_s and φ_v was 0.96 ($p < 0.005$). The authors concluded that a method based on the summation of the

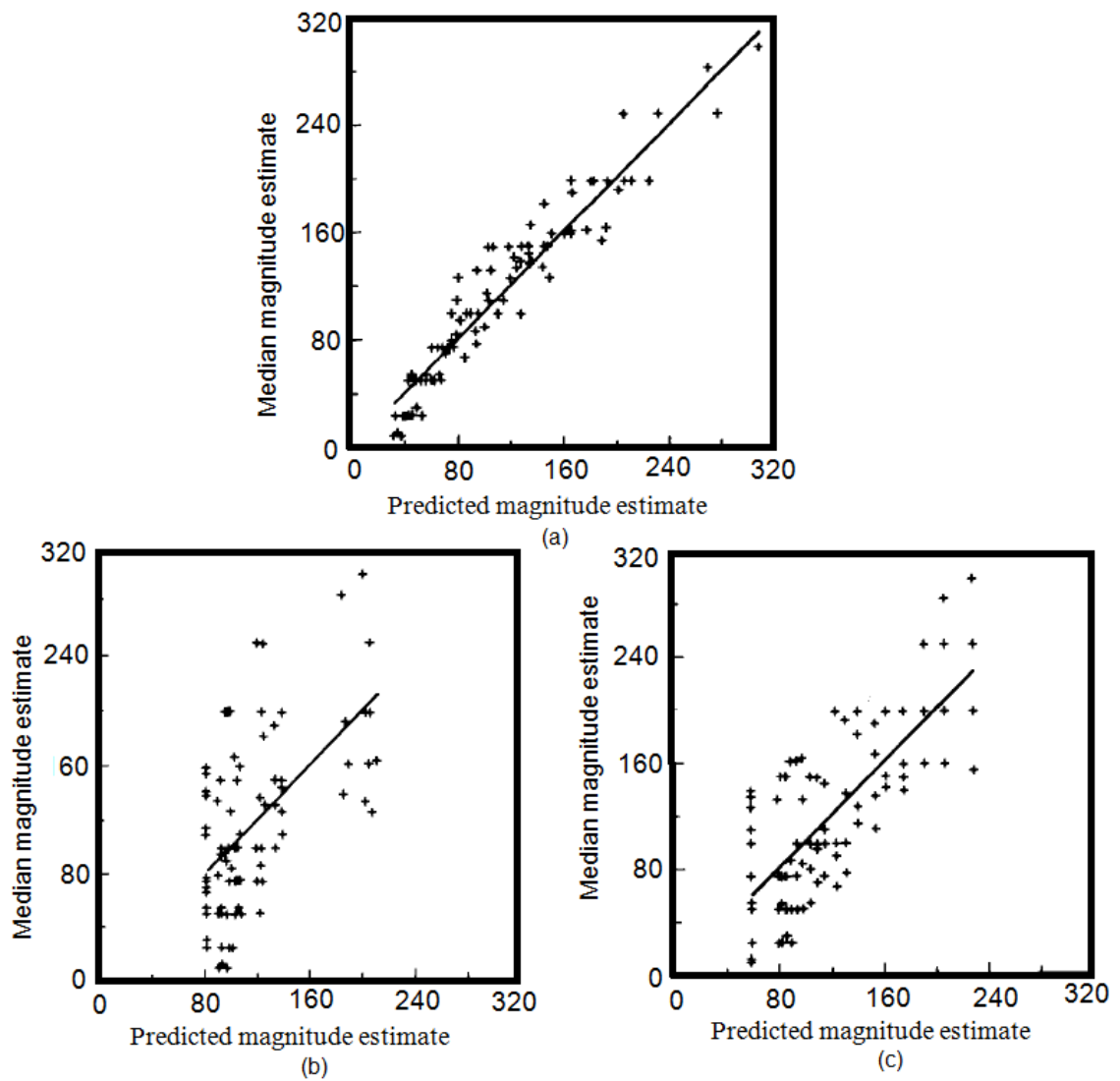


Figure 2.14 Comparison of median magnitude estimates with predicted magnitude estimates

given by: a) $\psi = 22.7 + 243\varphi_v^{1.18} + 0.265\varphi_s^{0.036}$, b) $\psi = 82.2 + 240\varphi_v^{1.18}$, and c)

$$\psi = 58.8 + 0.263\varphi_v^{0.036} \quad (\text{adapted from Howarth and Griffin, 1991}).$$

individual effects of the two stimuli provided a more accurate prediction of the total annoyance (disturbance) than that based on either noise or vibration alone, as shown in Figure 2.14.

Paulsen and Kastka (1995) investigated the combined effects of noise and whole-body vibration on subjective intensity and annoyance (see also Section 2.3.4). The noise and vibration produced by a passing tram and a work hammermill were recorded synchronously in a living room of a building nearby. Four experiments were conducted to rate the intensity and annoyance of: a) the vibration of a tram (three sessions), b) the vibration of a hammermill (three sessions), c) the noise of a tram and of a hammermill (one session each), and d) the overall situation of a tram and a hammermill (one session each). Each experiment involved sixteen subjects, and each subject participated in one experiment only. Each session consisted of sixteen combinations of four levels of noise and four magnitudes of vibration (none, low, medium and strong between 28 to 61 dBA SPL, and between 0.03 to 0.4 mm/s r.m.s. velocity). Each stimulus lasted 16 s and was described as the 'environment stimuli' to be rated on the 9-point scales from 0 (not perceptible/not at all disturbing) to 9 (extremely strong/unbearable disturbing).

Results of the first and second experiment indicated that the vibration annoyance was dependent on the magnitude of vibration and influenced by the type and meaning of vibration, but was not influenced by simultaneous noise. Results of the third experiment indicated that the noise annoyance depended on the level of noise and was influenced by simultaneous vibration. Results of the fourth experiment indicated the total annoyance was dominated by the level of noise, and the effect of vibration on the total annoyance was greater than that on the noise annoyance. The equations of total annoyance produced by combined noise and vibration were determined by the summation of individual annoyance as:

$$\psi = -0.15 + 1.58 \log_{10}(\nu_{\text{rms}}) + 0.11 L_{\text{Aeq}} \quad (2.41)$$

for tram noise and vibration with a correlation coefficient of 0.67 ($p < 0.01$), and

$$\psi = -0.33 + 1.64 \log_{10}(\nu_{\text{rms}}) + 0.12 L_{\text{Aeq}} \quad (2.42)$$

for hammermill noise and vibration with correlation coefficient of 0.70 ($p < 0.01$). The validity was restricted to the range of the stimuli employed in the study.

Paulsen and Kastka (1995) also reported the interactions among the 'noise', 'vibration' and 'subject'. The inter-subject variability (i.e., the influence of 'subject') was greater in the judgement of vibration than in the other experiments. The judgement of vibration was not influenced by noise if subjects were asked for the 'vibration', whereas the judgement of noise was dominated by noise but influenced by vibration if subjects were asked for the 'noise' and for the 'overall situation'. The influence of vibration was greater when subjects were asked for the 'overall situation' than when subjects were asked for the 'noise'.

Seidel *et al.* (1997) investigated the subjective response to combined noise and random low-frequency whole-body vibration. Twelve combinations of two levels of noise (75 and 83 dBA

SPL), two magnitudes of vibration (0.66 and 1.06 ms^{-2} r.m.s.), and three degrees of tonality (0 , 3 and 6 dB), were randomised for twelve subjects. Each exposure condition lasted 130 s , with 45 s for the physiological measurement and 85 s for the cross-modality match with the length of line to determine: 1) the loudness, 2) the intensity of vibration, 3) the noise annoyance, 4) the annoyance caused by the combined noise and vibration, and 5) the difficulty to drive a vehicle under the complicated conditions. Surprisingly, their results indicated that the loudness and annoyance produced by noise were not affected by simultaneous vibration, neither was the subjective intensity of vibration affected by simultaneous noise. However, the interaction and combined effects were significant on the judgement of annoyance and difficulty in driving due to the overall situation. Seidel *et al.* (1997) suggested a nonlinear relation to predict the annoyance caused by combined noise and vibration:

$$\psi = 0.0597NL + 0.0488VL + 0.050QT + 8.522, \quad (2.43)$$

where NL is the level of noise, VL is the level of vibration, and $QT = -136.99 + 0.0293 NL \times VL - 2 \times 10^{-6} \times (NL \times VL)^2$. All the conclusions were strictly restricted only to conditions similar to those tested in the experiment.

The interaction of noise and vibration regarding the subjective response to noise or vibration appears to be complex. An antagonistic (i.e., masking) effect of noise on judgements of vibration was found by Howarth and Griffin, (1990a), Miwa and Yonekawa (1973) and Sandover (1970), while a synergistic (i.e., additive) effect of noise on judgements of vibration was found by Howarth and Griffin (1990a) and Seidel *et al.* (1989). A synergistic effect of vibration on judgements of noise was found by Paulsen and Kastka (1995). However, Howarth and Griffin (1990a) indicated the noise annoyance was not influenced by vibration, Paulsen and Kastka (1995) indicated the vibration annoyance was not influenced by noise, and Seidel *et al.* (1997) indicated there was no effect of noise on vibration, or vibration on noise. It seems whether the antagonistic effect or synergistic effect was found depends on the relative magnitudes of noise and vibration.

The total discomfort produced by combined noise and vibration was generally greater than that produced by separate noise or vibration. Innocent and Sandover (1972), Dempsey *et al.* (1976, 1979a) and Leatherwood (1979) suggested that the discomfort caused by combined noise and vibration equals to the summated discomfort caused by noise and vibration acting separately. However, other studies indicated the subjective response to combined noise and vibration was complex. Different explanations of the combined effects of noise and vibration on the subjective judgements, and different approximations with multiple regression approaches to the combined annoyance (discomfort) were proposed in different studies (Howarth and Griffin, 1990a, 1991; Leatherwood *et al.*, 1984; Paulsen and Kastka, 1995; Seidel *et al.*, 1990, 1997). The contribution of noise and vibration generally depends on their relative magnitudes.

2.5 Discussion and Conclusion

The slope, $20(n_v/n_s)$, in the subjective equivalence equation (i.e., Equation (2.23)) indicating the relative effects of noise and whole-body vibration on sensation of comfort, can be anticipated from previous determinations of the exponent for noise, n_s , and the exponent for vibration, n_v , in the power functions (i.e., Equations (2.10) and (2.15)). Different slopes can be anticipated by using different values of n_v and n_s obtained in previous studies. For example, if the unity value of n_v (suggested by Fothergill and Griffin, 1977) and a commonly used value 0.67 of n_s (proposed by Stevens, 1986) were used, the slope would be around 30; if 0.71 is assumed for n_v (the average vibration exponent at frequencies between 2 to 50 Hz found by Morioka and Griffin, 2006), and 0.95 is assumed for n_s (the exponent of annoyance due to a 1000-Hz tone found by Hellman, 1983), the slope would be around 15. However, these values of n_v and n_s from different studies were obtained with different experimental conditions (different methods, stimuli, subjects, etc.), so the slopes predicted by n_v and n_s from such unrelated experiments might not be appropriate. A preliminary study was designed to determine the slope both from the subjective equivalence between noise and vibration in cars, and from the ratio of n_s and n_v (Chapter 5) obtained in the same experiment.

The value of the slope, $20(n_v/n_s)$, can be determined directly from experimental studies of the subjective equivalence between noise and vibration. Subjective responses to combined noise and vibration have been studied using artificial (e.g., sinusoidal or random) stimuli and reproductions of environmental stimuli (e.g., Fleming and Griffin, 1975; Hempstock and Saunders, 1973, 1976; Howarth and Griffin, 1990b; Kjellberg *et al.*, 1985; Paulsen and Kastka, 1995). Calculations of the physical magnitudes of noise and vibration that are subjectively equivalent show a wide range of values for $20(n_v/n_s)$ in different studies, for example 33.0 for sinusoidal stimuli (Fleming and Griffin, 1975), 29.3 for reproductions of noise and vibration in buildings near a railway (Howarth and Griffin, 1990b), 40.0 for broad-band noise and vibration of forklift trucks (Kjellberg *et al.*, 1985), 14.4 for noise and vibration recorded in a flat during the passing of a nearby tram (Paulsen and Kastka, 1995); and in the same study, for example 21.3 for matching bandwidth noise with sinusoidal vibration, and 43.5 for matching vibration with noise (Hempstock and Saunders, 1976).

Different values of $20(n_v/n_s)$ might arise for several reasons: the effect may be real and reflect real changes in the rates of growth with different stimuli, or it may be artefactual (e.g., due to different psychophysical methods, range effects, order of presenting stimuli, etc.) and reflect the methods used in the different experiments. The variation could alternatively reflect an interaction (e.g., masking) in which judgements of noise (or vibration) are affected by the presence of vibration (or noise). The limited number of studies currently available show divergent results but insufficient information to understand the causes of the differences. A study was designed to determine the subjective equivalence between noise and vibration by judging the discomfort caused by different levels of noise relative to discomfort caused by different magnitudes of

vibration, and judging vibration relative to noise, when the noise and vibration stimuli were presented simultaneously and sequentially (Chapter 6).

Although the subjective equivalence between noise and vibration in terms of SEL and VDV (Equation 2.23) instead of SPL and r.m.s. acceleration (Equation 2.22) was suggested for noise and vibration of variable duration (Howarth and Griffin, 1990b), the slopes $20(n_v/n_s)$ in the equivalence equation might still depend on the duration of the stimuli because the standardised time-dependency used to express exposure to noise in the SEL (International Organization for Standardization, 2003a) differs from the time-dependency used to express exposure to vibration in the VDV (British Standards Institution, 1987; and International Organization for Standardization, 1997). With stimuli of constant magnitude, the SEL increases by 3 dB (i.e., $\sqrt{2} \approx 41\%$) when the duration of noise doubles, whereas VDV increases by only 1.5 dB (i.e., $\sqrt[3]{2} \approx 19\%$) when the duration of vibration doubles. A study was designed to investigate how the subjective equivalence of bandwidth random noise and vibration depends on the durations of the stimuli (Chapter 7).

The findings on the influence of noise on the subjective response to vibration and the influence of vibration on the subjective response to noise in previous studies are not in agreement. The psychophysical relationships between the subjective magnitude and physical magnitudes to predict the total annoyance (discomfort) caused by combined noise and vibration proposed in previous studies may be applied with discretion. Further work is needed to understand and quantify the interaction and combined effects between noise and vibration on the sensation of comfort. A study was designed to investigate the effects of noise on judgements of vibration discomfort, the effects of vibration on judgements of noise discomfort, and the total discomfort caused by combined noise and vibration (Chapter 9).

The method of AME (Poulton, 1968, 1979; Stevens, 1971, 1986) was employed to obtain directly noise discomfort, vibration discomfort, and their combined discomfort in Chapter 9. The AME was relatively free of biases (Zwislocki and Goodman, 1980), but might have greater response variability than the RME (Mellers, 1983). A study was conducted to investigate the reliability of two methods of magnitude estimation, RME and AME, in rating discomfort associated with noise and whole-body vibration in advance to the discomfort study (Chapter 8).

Both the sounds and vibrations contribute to the perceived quality of a car. Perceptions can also be influenced by how the sounds and motions change in response to driver demands, such as gear and throttle changes. When in a car, drivers perceive how sounds and motions change as a consequence of their actions, which can be described as the 'vehicle responsiveness'; whereas passengers are they are often unaware of driver commands, so more likely to be influenced by their perception of the comfort than that of responsiveness. There are no known studies comparing such different perceptions of drivers and passenger to the combined motions and sounds in a car. A study was designed to investigate how changes in sound and motion in a car consequent upon driver commands affect the perception of 'responsiveness' and 'discomfort' (Chapter 4).

The literature review of previous studies reveals that there is inadequate information to understand completely the subjective response to simultaneous noise and whole-body vibration in cars. The main objective of the present study is to understand the effects of noise on vibration discomfort, the effects of vibration on noise discomfort, and the combined effects of noise and vibration on the sensation of comfort. The following information is thought to be required to achieve the main objective based on the literature review:

- 1) To investigate the effects of sound level and vibration magnitude on the relative discomfort of noise and vibration in a car.
- 2) To investigate the effects of duration of sound and vibration on the relative discomfort of noise and vibration.
- 3) To investigate the discomfort caused by noise, the discomfort caused by vibration, and their contribution to the total discomfort caused by combined noise and vibration.

Chapter 3 Apparatus and Analysis

3.1 Introduction

This chapter describes the apparatus and analysis employed when measuring and recording vibration, noise and vision in cars, the apparatus used to reproduce vibration and noise in the laboratory, and the statistical analysis methods employed in this thesis.

All experiments were carried out in the main laboratory of the Human Factors Research Unit (Room 1041, Building 19), the Institute of Sound and Vibration Research, University of Southampton. All experiments were approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton. Informed consent to participate in the experiment was given by all subjects.

3.2 Field measurements

3.2.1 Vibration

Measurements in the field were made in different types of car (right hand drive). Vibration on the floor was measured using six accelerometers (Silicon Designs Inc., Washington, USA; Model 2260-002 for x - and y - axes, and 2260-005 for z - axis) attached to aluminum blocks that were rigidly mounted to the floor attachment points of the front passenger seat (Figure 3.1): at the outside-front seat attachment point (for x -, y - and z -axes), at the inside-front seat attachment point (for x - and z -axes), and at the outside-rear seat attachment point (for z -axis).

Accelerations on the front passenger seat surface (z -axis) and backrest (x -, y - and z -axes) were measured using two accelerometers (Entran Devices, New Jersey, USA; Model EGCSY-240D-

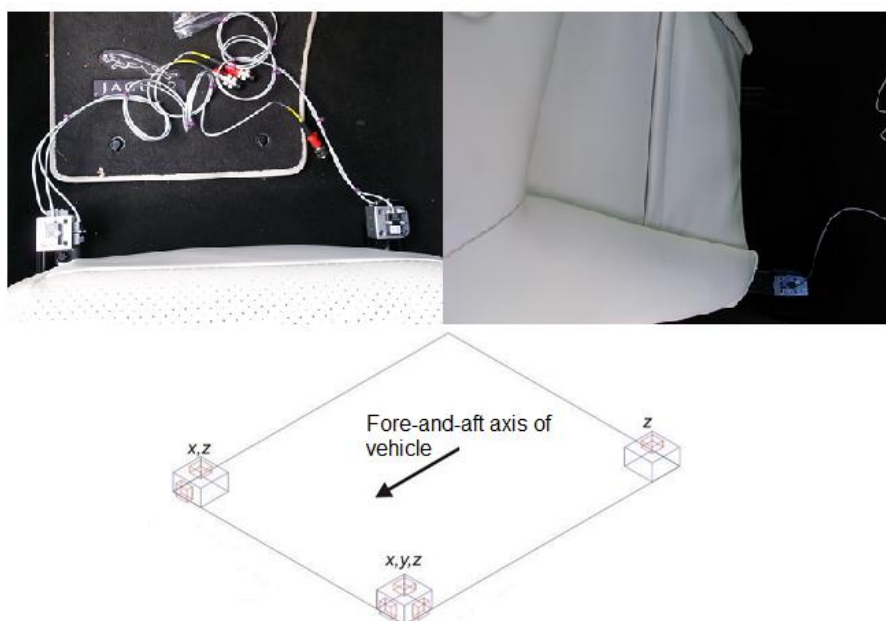


Figure 3.1 Accelerometers mounted at the base of front passenger seat

10) moulded into two *HVLab* (Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, UK) SIT-pads (Figure 3.2). The backrest was inclined at 25 degrees relative to the vertical of the head restraint pillar. The seat cushion was at an angle of 20 degrees to the horizontal. A SIT-pad was located on the seat surface under the passenger so that the ischial tuberosities were positioned either side of the raised area in the centre of the pad. A SIT-pad was placed on the backrest so that the flat side faced outwards and the centre of the pad was located at 320 mm above the surface of the seat.

3.2.2 Sound and vision

Mono sound was measured and recorded using a sound level meter (Rion Co., Model NL-28, S/N 00960045) at the head position of the front passenger. The visual scene was captured by a Canon MV750i E (Canon, Japan; S/N 234863512818) digital camcorder. The camera was mounted internally to the windscreen along the passenger side and 20 cm from the bottom.

A 16-channel *HVLab* data acquisition and analysis system (Version 3.81) was used to acquire the signals from the accelerometers. The *HVLab* system, sound level meter and the digital camcorder were connected to a laptop (Figure 3.3) as that the vibration, sound and vision were acquired and recorded synchronously using the *HVLab HRV Matlab* toolbox (Version 1.0), Data acquisition toolbox and Image acquisition toolbox in MATLAB (MathWorks, Massachusetts, USA; Version 2009a). The vibration signals were acquired at 512 samples per second, the sound signals were acquired at 16 Bit 44.1 kHz, and the visual signals were acquired at 27 fps.

3.3 Laboratory apparatus

3.3.1 Horizontal vibration

A hydraulic vibrator capable of a horizontal displacement of 1-metre (peak to peak) was used in Experiment 1 to produce horizontal vibration. A 1500 × 1000 mm aluminium alloy platform was mounted on the upper carriage frame driven by a servo-hydraulic actuator. A rigid wooden rigid seat with a backrest was rigidly mounted on the platform to allow fore-and-aft motion. A steering wheel was also fixed on the platform. The positions of the seat, footrest and steering wheel and related angles are shown in Figure 3.4.

The vibrator was controlled by an STI Tiab Digital Control System (Servo Technique International, Herts, UK; Version v2.01). A piezoresistive accelerometer (Entran Devices, New Jersey, USA; Model EGCSY-240D*-10) was mounted on the wooden seat to monitor the acceleration. The test signals were generated and acquired at 512 samples per second using an *HVLab* data acquisition and analysis system (Version 3.81). The background signals were supplied by a signal generator (Thurlby Thandar Instruments, Huntingdon, UK; Model TG501). The test and background signals were summed then low-pass filtered at 40 Hz before reaching to the digital controller.



Figure 3.2 Accelerometers mounted on the front passenger seat.



Figure 3.3 Acquisition system

The distortion of the 1-m horizontal vibrator was measured by Thuong (2011) using low, medium, and high magnitudes of vibration at each preferred 1/3 octave frequency in the range 0.5 to 16 Hz. The frequency-weighted distortion (using weighting W_d in BS 6841:1987) was less than 15% at 1 Hz, and less than 5% for frequencies greater than 2 Hz. The magnitude of the background vibration on the 1-metre horizontal vibrator without an input signal present was 0.021 ms^{-2} r.m.s. and not perceptible.

3.3.2 Vertical vibration

A hydraulic vibrator capable of a vertical displacement of 1-metre (peak to peak) was used in the Experiments 2 to 6 to produce vertical vibration. A 1500×900 mm aluminium alloy platform was mounted on the top of the piston rod driven by the servo-hydraulic actuator and fitted with

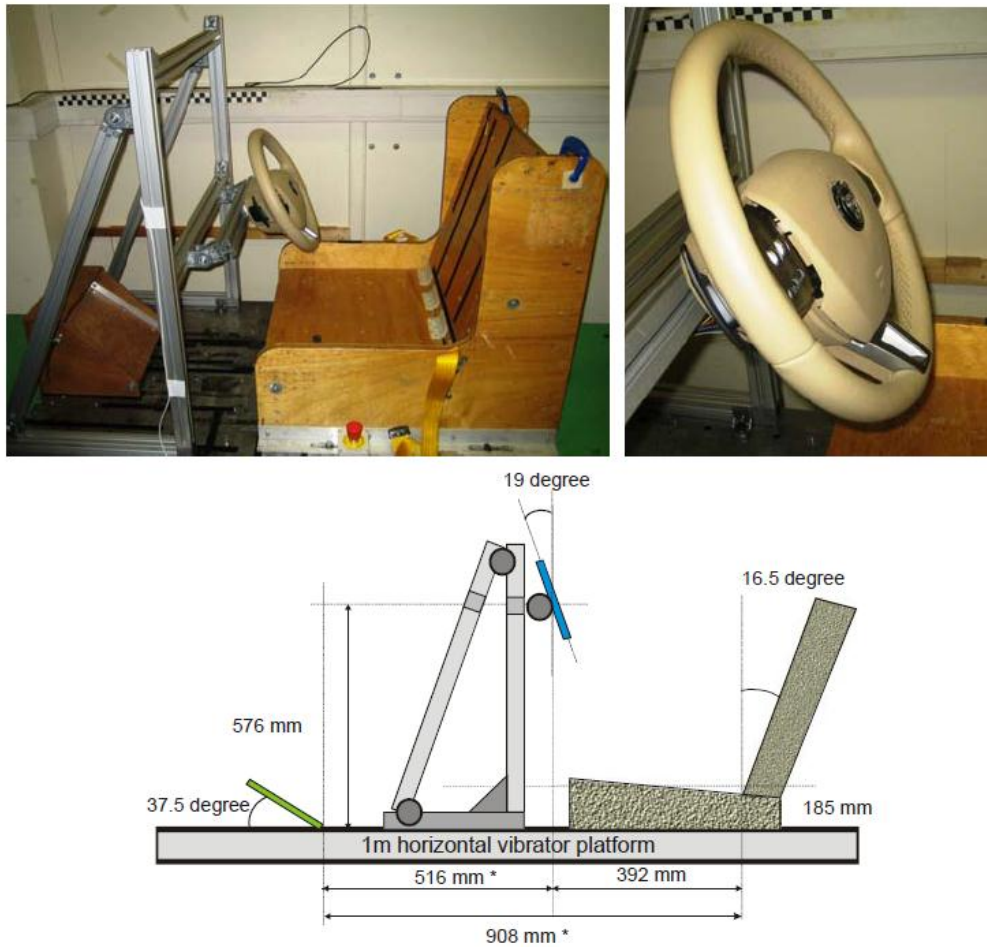


Figure 3.4 Dimensions of the test rig on the 1-metre horizontal vibrator.

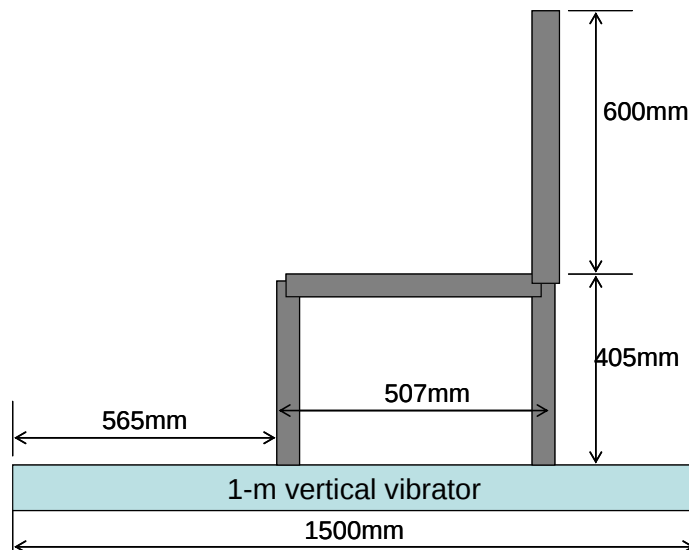


Figure 3.5 Dimensions of the test rig on the 1-metre vertical vibrator.

an anti-rotation assembly. A rigid flat wooden surface was secured to a rigid aluminium-framed (for Experiment 2 and 3) or steel-framed seat (for Experiment 4, 5 and 6) with a rigid vertical flat backrest mounted on the platform (Figure 3.5).

The vibrator was controlled by a Pulsar Digital Controller (Servotest Test Systems, Egham, UK). A piezoresistive accelerometer (Entran Devices, New Jersey, USA; Model EGCS-10-IV10/L4M) secured to the seat monitored the acceleration. The vibration signals were generated and acquired in the Pulsar software (Version 1.4) provided by Servotest Test Systems at 256 samples per second and low-pass filtered at 40 Hz.

The weighted distortion (using frequency weighting W_b in BS 6841:1987) was less than 13% at 1 Hz, less than 10% for frequencies between 2 and 8 Hz, and less than 5% for frequencies higher than 8 Hz (Thuong, 2011). The magnitude of background vibration without input signal presented on the 1-metre vertical vibrator was 0.003 ms^{-2} r.m.s. and not perceptible.

3.3.3 Sound

In Experiment 1, the test noise signals were generated using the *HVLab* data acquisition and analysis system (Version 3.81); in the other experiments, the test noise signals were generated and controlled using Adobe Audition 3 (Adobe Systems, California, USA) software and an E-MU 0404 USB 2.0 Audio/MIDI Interface (Creative, Singapore). Two pairs of headphones were used: Sennheiser eH150 (Sennheiser electronic GmbH & Co. KG, German) for the first experiment and ATH M50 (Audio-Technica Corporation, Japan) for the other experiments.

Sound levels from the headphones were calibrated and measured using a 'Kemar' (Knowles Electronics Manikin for Acoustic Research; Industrial Research Products Inc., Illinois, USA; Type DB4004, S/N 1045) artificial manikin (Figure 3.6). The Kemar incorporates an ear simulator (G.R.A.S. Sound & Vibration A/S, Denmark; Type IEC 700, S/N 100376) that houses a microphone (G.R.A.S. Type 40AG, S/N 88469) to measure sound levels at the eardrum



Figure 3.6 Kemar in measurement

position. A B&K calibrator (Brüel & Kjær Sound & Vibration Measurement A/S, Denmark; Type 4231, S/N 2592278) and a B&K sound level meter (Type 2250, S/N 2590569) were used. The SPLs were calculated using the diffuse field in BS EN ISO 11904-2 (British Standards Institution; 2004) and applying the A-weighting to the 1/3 octave band spectra measured by the B&K 2250 sound level meter.

The levels of background noise emitted from the horizontal and vertical vibrators were less than 52 dBA, when measured in the ear wearing the headphones. The ambient noise intermittently reached 60 dBA when a hydraulic scavenge pump was running, but it was not related to the vibration and noise stimuli.

3.3.4 Sitting posture

In Experiment 1, subjects were instructed to sit on a wooden rigid seat with their backs on the backrest, feet on the footrest, either holding the steering wheel (as drivers) or not (as passengers). The subjects wore a blindfold and a pair of headphones. In the other experiments, subjects were instructed to sit with a comfortable upright posture without contact with the backrest. The subjects kept their eyes closed and wear the headphones. The examples of the sitting postures during the experiments are shown in Figure 3.7.

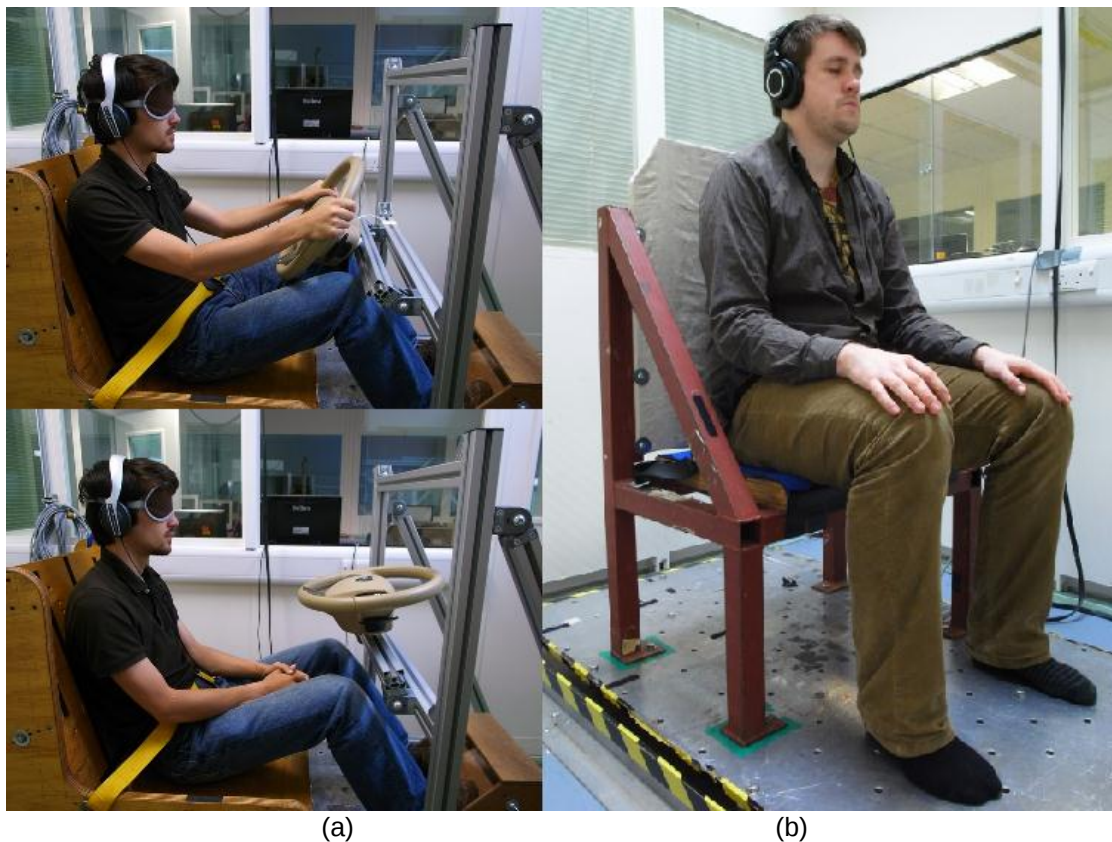


Figure 3.7 Body postures adopted by subjects: (a) Experiment 1 (b) Experiment 2 to 6.

3.4 Statistical analysis methods

Piface (version 1.72) was used for statistical power calculations in planning statistical experiments. MATLAB (version 2009a) and SPSS Statistics (version 17.0) were used to perform statistical analysis on the data.

To avoid making assumptions on the distribution of the population, nonparametric statistical tests were used (Siegel and Castellan, 1988). The tests used for the study are shown in Table 3.1.

Table 3.1 Nonparametric statistical tests used in the study

Case	Statistical test
2 related samples	Wilcoxon signed ranks test
k related samples	Friedman two-way analysis of variance
Correlation between two variables	Spearman rank-order correlation coefficient

Chapter 4 Effect of delays during gear changes on responsiveness and discomfort

4.1 Introduction

Instead of solely reducing the acoustical energy emitted by a product, it is becoming recognised that acoustic emissions have other characteristics to consider, such as their time structures and frequency spectra. Such considerations led to the term ‘sound quality’ that has been defined as the “*adequacy of a sound in the context of a specific technical goal and/or task*” (Blauert and Jekosch, 1997). The term ‘compatibility’ has also been used in this context, especially with regard to sounds accompanying the actions of users of products (e.g., the driver of a car). An analogous concept of quality may also be appropriate to the evaluation and assessment of vibration, where the ‘vibration quality’ of a product may be indicated by a judgement, such as a value on a bipolar scale from ‘bad’ to ‘good’.

The noise and vibration environment in a car contain information that informs drivers and passengers about the state of the car and the road. The sounds and motions contribute to the perceived quality of a car. Perceptions can also be influenced by how the sounds and motions change in response to driver demands, such as gear and throttle changes.

Drivers perceive how sounds and motions change as a consequence of their actions. A slow response to a driver command may be interpreted as a sluggish vehicle, whereas an overly quick response may be perceived as an edgy vehicle. Delays between commands (e.g., throttle and gear lever movements) and the associated responses (e.g., perceptible changes in car movement or noise) are expected to contribute to driver perception of vehicle responsiveness. It may be expected that delays between variations in sound and motion will also influence a feeling of vehicle quality. In a previous study of how driver perceptions of a gear shift depends on delays between driver commands and the consequent changes in motions and sounds, it was found that when the motion and sound were delayed equally, the responsiveness decreased with increasing delay, and that when the sound and motion were delayed differently, the judgements of responsiveness were more greatly influenced by the motion than the sound, leading to high correlations between motion delay and responsiveness (Morioka and Griffin, 2007).

Passengers are often unaware of driver commands, so as the motions and sounds change as a consequence of driver actions, passengers are more likely to be influenced by their perceptions of the comfort than their perceptions of the responsiveness of the vehicle. The changes in motion and sound that drivers associate with a vehicle having ‘good responsiveness’ may not be the same changes that passengers associate with a vehicle having ‘good comfort’. There are no known studies comparing the different perceptions of drivers and passengers to the combined motions and sounds in a car.

The study reported in this chapter was designed to investigate how driver and passenger perceptions of changes in motion and sound in a car consequent upon driver commands affect perceptions of vehicle responsiveness and vehicle comfort. It was hypothesised that driver perceptions of a gear-shift would depend on delays between the driver command and the consequent changes in motion and sound, but that passenger perceptions of the same motions and sounds would depend on delays between motion and sound (assuming they are unaware of the moment when the driver initiates the command to change gear). It was also hypothesised that passenger perceptions of discomfort would depend on the level of sound.

4.2 Method

4.2.1 Subjects

Twelve male subjects with median age 26 yrs (range 25 to 45 yrs), stature 170.5 cm (range 165 to 185 cm), and weight 60 kg (range 55 to 85 kg) participated in the experiment. The subjects were students or staff of the University of Southampton, with no history of occupational exposure to whole-body vibration or hand-transmitted vibration. All subjects had driving experience.

4.2.2 Stimuli

The changes in fore-and-aft motion and engine noise associated with a gear-shift were based on stimuli recorded in cars. Simplified motion and sound stimuli were developed so as to ensure that subjective evaluations of responsiveness were judged for a single definable event having only an initial shift motion and an associated sound rather than secondary motions and sounds (Morioka and Griffin, 2007).

The motion stimulus representing a gear-shift consisted of a squared half-sine motion having a fundamental frequency of 4 Hz at 1 ms^{-2} peak followed by squared half-sine motion having a fundamental frequency of 1 Hz at 0.125 ms^{-2} peak. The two half-sine motions were in opposite directions, as shown in Figure 4.1. This motion allowed the velocity to be zero at the start and the end of the stimulus. Seven motion stimuli, all with the same waveform, were generated with a series of time delays ranging from 150 to 450 ms in 50 ms steps.

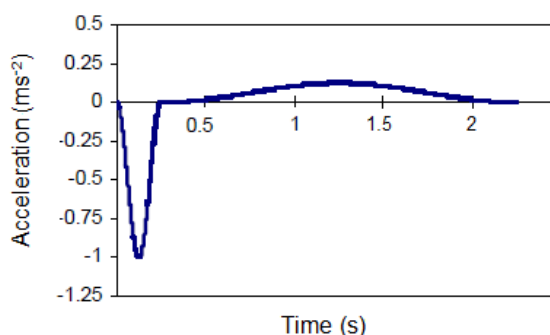


Figure 4.1 Time history of the motion acceleration.

Table 4.1 Characteristics of the sound and motion stimuli.

	Stimulus	Frequency	VDV and SEL
1.	Gear-shift motion	Squared half-sine of 4 Hz and 1 Hz	0.27 ($\text{ms}^{-1.75}$)
2.	Background vibration	16 Hz sine	0.12 ($\text{ms}^{-1.75}$)
3.	Combined vibration	Stimuli 1 and 2	0.27 ($\text{ms}^{-1.75}$)
4.	Gear-shift sound	Random sound (315-500 Hz) with a cosine taper	66.0, 70.7, 75.7 dBA
5.	Background noise	Band pass filtered white noise (50-315 Hz)	59.7 dBA
6.	Combined noise	Stimuli 4 and 5	71.1, 73.2, 76.6 dBA

The sound stimulus associated with a gear-shift consisted of Gaussian random sound (bandwidth 315 to 500 Hz) of 2-s duration with a cosine taper commencing after 1 s. Three sound stimuli were generated, with SPLs of 56.0, 60.7, and 65.7 dBA. For each of the three sound levels, seven sound stimuli were generated with a series of time delays ranging from 150 to 450 ms in 50-ms steps.

In addition to the motion and sound stimuli representing the gear-shifts, there was background vibration and background noise simulating the vibration and noise environment in a car. The background vibration and background noise persisted continuously without a break throughout each session of the experiment. Sinusoidal fore-and-aft vibration of 16 Hz at 0.1 ms^{-2} r.m.s. represented the background vibration. Band-pass filtered white noise from 50 to 315 Hz presented at 59.7 dBA SPL represented the background noise.

Assuming exposure duration of 10 s for each trial, the characteristics of the sounds and vibrations used in the experiment are shown in Table 4.1. The VDV's were calculated at the seat and the back by using frequency weightings W_d and W_c (British Standards Institution, 1987). The SELs were measured by using the Kemar system (International Organization for Standardization, 2009).

4.2.3 Procedure

Subjective judgements of 'responsiveness' (for drivers) and 'discomfort' (for passengers) were obtained using the method of relative magnitude estimation (RME). Each subject was presented with a reference stimulus followed by a test stimulus.

In the judgements of responsiveness, the reference stimulus consisted of a fixed combination of motion and sound: the gear-shift motion and the 70.7 dBA gear-shift sound, both commencing 300 ms after the subject pressed the gear-shift paddle. The test stimuli were the 49 combinations of the seven test motion stimuli (with delays of 150 to 450 ms in 50-ms steps) and the seven test sounds (with delays of 150 to 450 ms in 50-ms steps). The 49 test stimuli were presented to subjects in independent random orders. The 'driver subjects' were instructed to judge the responsiveness associated with each test stimulus relative to the reference stimulus representing a responsiveness of 100.

In the judgements of discomfort, the reference stimulus consisted of a gear-shift motion commencing simultaneously with a 70.7 dBA gear-shift sound. The test stimuli consisted of 39 combinations of the motion and sound stimuli: thirteen delays between motion and sound (-300, -250, -200, -150, -100, -50, 0, 50, 100, 150, 200, 250, 300 ms, where a negative delay represents motion before sound) with three sound levels (56.0, 60.7, and 65.7 dBA SPL). The 39 test stimuli were presented to subjects in independent random orders. The 'passenger subjects' were instructed to rate the discomfort caused by each test stimulus relative to the reference stimulus representing a discomfort of 100.

For 'driver' perceptions of responsiveness, the reference stimulus and the test stimulus were activated by the subjects pressing the left gear paddle on the steering wheel. An auditory cue (a beep sound) was presented to the subjects via headphones to inform them when they could press the gear paddle to initiate a reference or test stimulus. For 'passenger' perceptions of discomfort, the reference stimulus and the test stimulus were presented to the subjects without the auditory cue, since car passengers do not normally know precisely when a gear shift is initiated.

Subjects were provided with written instructions (Appendix A1) and then practiced magnitude estimation (by judging the lengths of lines drawn on paper and by judging six stimuli to be used in the experiment). Six of the twelve subjects were first tested as drivers and the other six were first tested as passengers.

4.3 Results

4.3.1 Responsiveness

Median subjective ratings of responsiveness as a function of delay in the simultaneous presentation of motion and sound are shown in Figure 4.2. When the motion and sound stimuli were presented with an equal delay after a gear-shift (i.e. they commenced simultaneously at

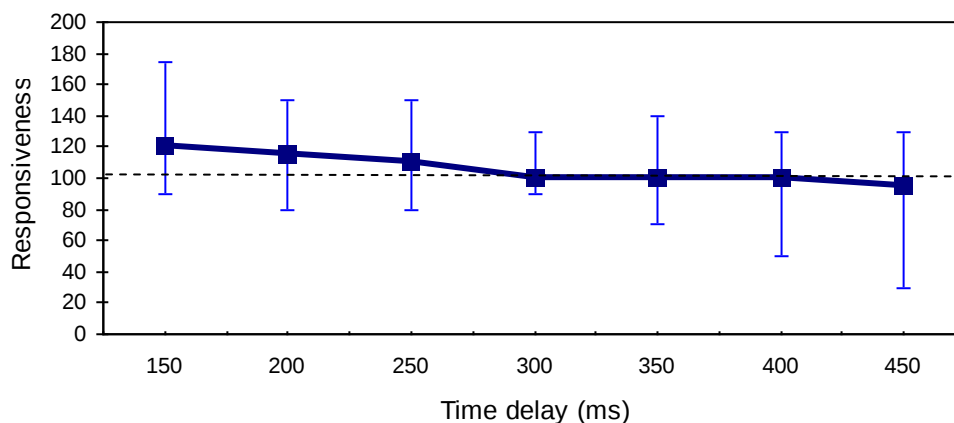


Figure 4.2 Subjective ratings of responsiveness for simultaneous presentation of motion and sound relative to reference delay of 300 ms (medians and inter-quartile ranges).

some time after subjects' clicked the paddle), the ratings of responsiveness were significantly dependent on the delay (Friedman, $p < 0.05$), and generally decreased with increasing delay. The maximum median responsiveness was obtained with a delay of 150 ms and the minimum median responsiveness was obtained with a delay of 450 ms (Wilcoxon, $p = 0.05$). Although the median responsiveness fell progressively with increasing delay, there were no significant changes in the range 200 to 450 ms (Wilcoxon, $p > 0.05$).

At none of the seven motion delays, were the ratings of responsiveness significantly influenced by the sound delay (Friedman, $p > 0.30$). However, with each of the seven sound delays, the ratings of responsiveness were significantly increased with reduced motion delay (Friedman, $p < 0.05$). The median subjective judgments of responsiveness for all 49 combinations of the 7 sound delays and the seven motion delays are summarised in Figure 4.3. It is evident that responsiveness decreased with increased stimulus delay, with responsiveness more greatly influenced by the motion delay than the sound delay.

4.3.2 Discomfort

With each of the thirteen delays between the motion and sound stimuli, subjective ratings of discomfort were significantly increased by increases in the sound level (Friedman, $p < 0.001$). However, at each of the three levels of sound, there was no change in the discomfort ratings

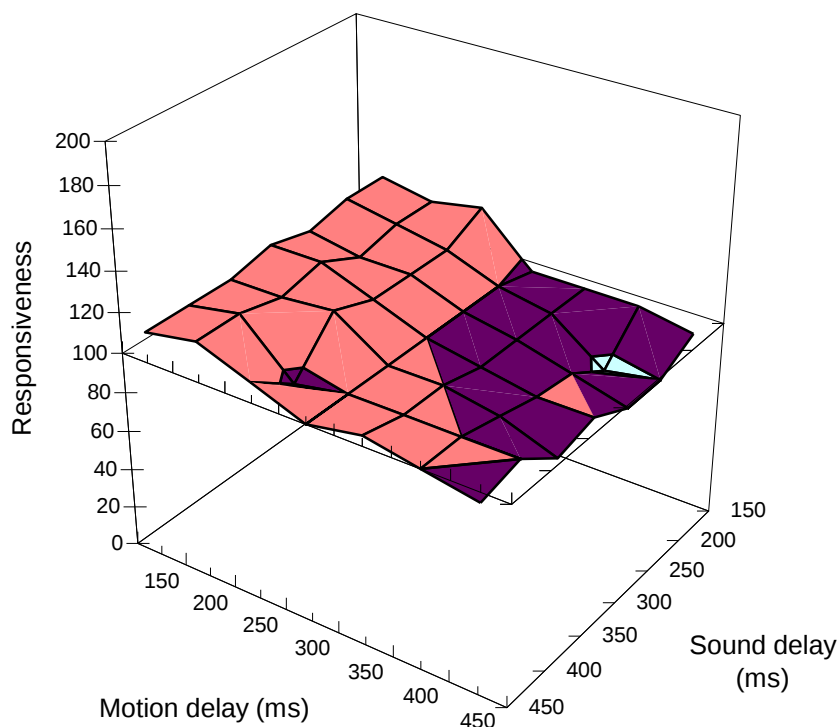


Figure 4.3 Median subjective ratings of responsiveness (relative to 300 ms simultaneous delay) for all 49 combinations of motion delay and sound delay.

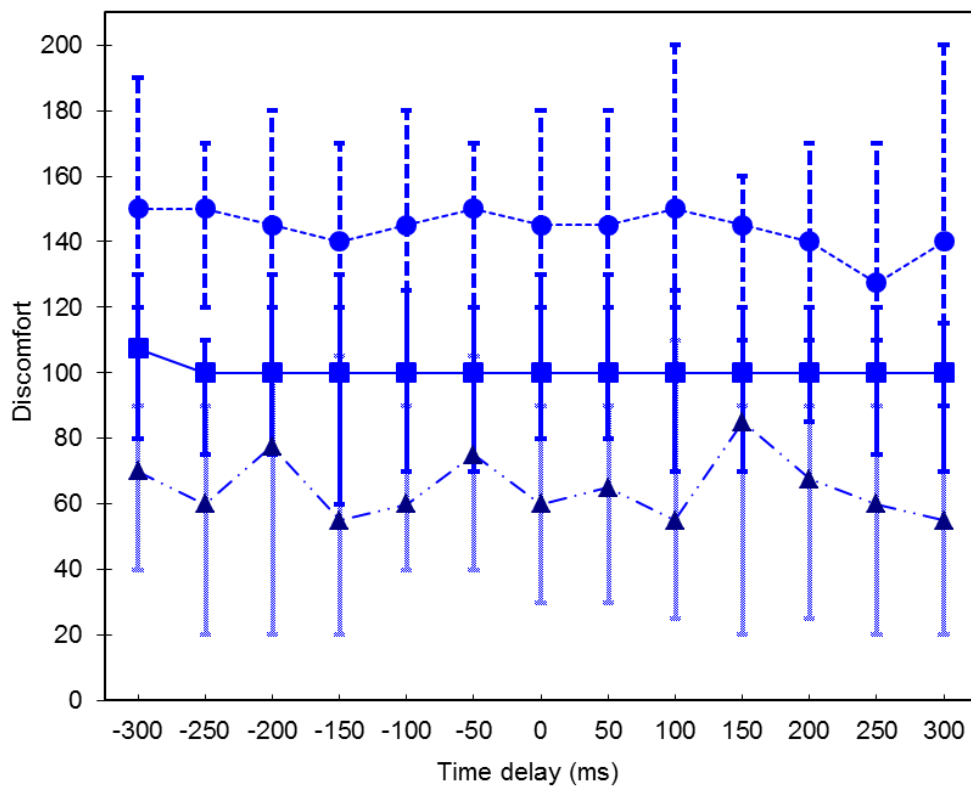


Figure 4.4 Ratings of discomfort (medians and inter-quartile ranges) for different sound levels and different delays in the motion and sound stimuli. Negative delays indicate motion before sound. $\cdots \triangle \cdots L_{AE} = 66.0$ dBA, $\text{---} \blacksquare \text{---} L_{AE} = 70.7$ dBA, $\text{---} \bullet \text{---} L_{AE} = 75.7$ dBA.

due to variations in the delay (Friedman, $p > 0.18$). Median subjective ratings of discomfort for each SEL as a function of delay in the motion and sound stimuli are shown in Figure 4.4.

4.4 Discussion

The judgements of responsiveness show that when the motion and sound were delayed equally, the perceived responsiveness tended to decrease with increasing delay. When the motion and sound were delayed differently, judgements of responsiveness were dominated by the motion delay and not significantly affected by the sound delay. These results are consistent with the findings of Morioka and Griffin (2007). From Figure 4.3 it can be concluded that both findings are consistent with impressions of responsiveness being dominated by the perception of motion for the conditions investigated in this experiment.

The judgements indicate that the greatest impressions of responsiveness are obtained when the simultaneous delay in motion and sound is 150 ms, or possibly shorter. Subject 'action time' when clicking the paddle and the tactile response of the paddle may become influencing factors with such short delays: drivers may have difficulty judging differences in responsiveness shorter than about 150 ms unless they have clear cues as to when they have activated the gear-shift paddle.

There was no statistically significant change in responsiveness with delays between 200 and 450 ms, although there was a progress change. A possible explanation for the absence of a significant difference between 200 and 450 ms is that the method was too imprecise to determine whether subjects could discriminate between these stimuli (i.e., between 200, 250, 300, 350, 400, or 450-ms delays) and the reference stimulus (with a delay of 300 ms). The wide scatter evident in Figure 4.2 suggests that while some subjects found the task difficult, other subjects perceived large differences associated with variations in delay. Increased subject training or another method (e.g., paired comparison method) of obtaining subjective judgements may be appropriate.

The judgements of discomfort increased with increasing sound levels, and were independent of the delays between motion and sound, irrespective of whether the motion occurred before or after the sound. A possible explanation is that for the stimuli investigated the discomfort was dependent on the magnitude, frequency and duration of both the motion and the sound, but not the delay between the motion and the sound (Griffin, 1990). Nevertheless, there may be interactive effects between motion and sound that merit further investigation.

To create a good impression of responsiveness the findings suggest it is desirable for a car to respond to a gear-shift with simultaneous changes in motion and sound after a minimum delay (e.g., 150 ms). To create a good impression of comfort the findings indicate that a car should respond to a gear-shift with minimum increase in the level of sound. Although not studied here, standards for the evaluation of ride quality imply that for a good impression of comfort a car should respond to a gear-shift with minimum additional transient motion (e.g., British Standards Institution, 1987).

4.5 Conclusion

For the conditions investigated, the responsiveness ratings of 'drivers' decreased with increasing delay between a simulated gear-shift and the consequent changes in the motion and sound stimuli, with the ratings dominated by the delay in the motion when motion and sound were delayed independently. The discomfort ratings of 'passengers' increased with increasing sound levels, but were not affected by delays between the motion and sound representing a gear-shift.

Chapter 5 Effect of physical magnitudes on the relative discomfort of noise and vibration: I

5.1 Introduction

To understand subjective responses to combined noise and vibration it is helpful to know the relative importance of the two modalities. The subjective equivalence equation, which indicates the relative effects of noise and whole-body vibration on the comfort, can be written as (see also Section 2.3.4):

$$L_{AE} = k + 20(n_v/n_s) \log_{10}(a_{VDV}), \quad (5.1)$$

where k is a constant (dB). The relationship implies that when presented on a graph of $\log_{10}(a_{VDV})$ versus L_{AE} , the subjective equivalence between noise and vibration should have a slope, s , of $20(n_v/n_s)$.

The value of $20(n_v/n_s)$ can be anticipated from previous determinations of the growth function for noise, n_s , and the growth function for vibration, n_v . For vertical whole-body vibration, various values of the exponent, n_v , have been reported: between 0.86 and 1.04 with the mean value of 0.94 for frequencies in the range 3.5 to 20 Hz (Shoenberger and Harris, 1971), 0.93 for frequencies from 5 to 80 Hz (Jones and Saunders, 1974), the mean value of 1.05 for frequencies from 3 to 50 Hz (Clarke and Osborne, 1975), 1.04 to 1.47 for frequencies from 4 to 63 Hz (Howarth and Griffin, 1988), 1.18 for frequencies of 10 to 50 Hz (Howarth and Griffin, 1991) and 0.626 to 0.897 for frequencies between 2 and 50 Hz (Morioka and Griffin, 2006). The appropriate exponent seems to depend on the frequency of vibration and, perhaps, the magnitude of vibration.

For sound, an exponent of 0.68 was originally proposed to relate the subjective magnitude of loudness to the sound pressure of 1000-Hz tones (Stevens, 1969, 1986), and this value is widely quoted and has been recognized as the standard value ((International Organization for Standardization, 1959). Hellman (1983) obtained exponents of 0.63 and 0.92 for loudness, and 0.95 and 1.1 for annoyance, when judging subjective magnitude of low-pass noise with a 1000-Hz tone and a 3000-Hz tone. With two sets of 1000-Hz tone stimuli (narrow-range set with stimuli from 55 to 82 dB in 3-dB steps; wide-range set with 40, 43, 61 to 64 in 3-dB steps, 94, and 97 dB stimuli), Ward *et al.* (1996) obtained exponents of 0.411 and 0.244 for the narrow-range and the wide-range conditions, respectively when using category judgment, 0.483 and 0.324 when using AME, and 1.017 and 0.759 when using cross-modality matching to the apparent brightness of a light.

From the different exponents of n_v and n_s in previous studies, different slopes for the subjective equivalence between noise and vibration on a graph of $\log_{10}(a_{VDV})$ versus L_{AE} can be anticipated. For example, if the unity value of n_v (suggested by Fothergill and Griffin, 1977) and a commonly used value 0.68 of n_s (proposed by Stevens, 1986) were employed, the slope would be around

30 dB. If $n_v = 0.71$ (the average vibration exponent at frequencies between 2 to 50 Hz found by Morioka and Griffin, 2006), and $n_s = 0.95$ (exponent of annoyance due to a 1000-Hz tone found by Hellman 1983), then the slope would be around 15. However, these values for n_v and n_s were obtained with different experimental conditions (different methods, stimuli, subjects, etc.), so the slopes predicted by n_v and n_s from such unrelated experiments might not be appropriate.

The value of the slope, $20(n_v/n_s)$, can be determined directly from experimental studies of the subjective equivalence between noise and vibration. Subjective responses to combined noise and vibration have been studied using artificial stimuli (e.g. sinusoidal or random noise and vibration) and reproductions of environmental stimuli (e.g., Hempstock and Saunders, 1973, 1976; Fleming and Griffin, 1975; Kjellberg *et al.*, 1985; Howarth and Griffin, 1990b; Paulsen and Kastka, 1995; Parizet *et al.*, 2004). Calculations of the physical magnitudes of noise and vibration that are subjectively equivalent show a wide range of values for $20(n_v/n_s)$ in different studies, e.g., 33.0 for sinusoidal stimuli (Fleming and Griffin, 1975), 29.3 for reproductions of noise and vibration in buildings near a railway (Howarth and Griffin, 1990b), 40.0 for broad-band noise and vibration of forklift trucks (Kjellberg *et al.*, 1985), 14.4 for noise and vibration recorded in a flat during the passing of a nearby tram (Paulsen and Kastka, 1995); and even in the same study, e.g., 21.3 for matching bandwidth noise with sinusoidal vibration and 43.5 for matching vibration with noise (Hempstock and Saunders, 1976).

Different values for the exponents, n_v and n_s , and their ratio $20(n_v/n_s)$ might arise for several reasons: the effect may be real and reflect real changes in the rates of growth with different stimuli, or it may be artefactual (e.g. due to the use of different psychophysical methods, range effects, order of presenting stimuli, etc.) and reflect the methods used in the different experiments. The variation could alternatively reflect an interaction (e.g., masking) in which judgements of noise (or vibration) are affected by the presence of vibration (or noise). The limited number of studies currently available show divergent results but insufficient information to understand the causes of the differences.

Two studies were designed to determine the subjective equivalence of noise and vibration in the present chapter and the following chapter. The study reported in this chapter investigated the relative importance of noise and vibration to the sensation of comfort in two ways: (i) rate the discomfort produced by noise recorded in a car relative to the discomfort produced by vertical vibration in the car which was recorded at the same time, (ii) rate the discomfort of vertical vibration relative to the simultaneous noise in the car.

5.2 Method

5.2.1 Subjects

Twelve male subjects with median age 28 years (range 25 to 40 years), stature 172 cm (range 164 to 178 cm), and weight 67 kg (range 56 to 90 kg) volunteered to take part in the experiment. The subjects were students or staff of the University of Southampton.

5.2.2 Stimuli

Sound and vibration were measured and recorded inside a car (2171cc petrol engine, 4488 mm length, 1757 mm width, 1369 mm height, 2725 mm wheelbase, and 1890 kg gross vehicle weight). The details of the field measurements were described in Chapter 3, Section 3.2.

Synchronous noise and vibration of 4-s duration was selected with the car running at 40 mph on an asphalt road. The r.m.s. acceleration, a_{rms} , and VDV, a_{VDV} , of this vibration were 0.32 ms^{-2} and $0.63 \text{ ms}^{-1.75}$, respectively, using frequency weighting W_b (British Standards Institution, 1987; International Organization for Standardization, 1997); the A-weighted SPL, L_{Aeq} , and the A-weighted SEL, L_{AE} , were 65 and 71 dBA, respectively (International Organization for Standardization, 2003a).

The vibration and sound stimuli used in the experiment were developed from the selected sample by applying a cosine taper to the first and last 0.2 s. The time series and the frequency spectra of the vibration and sound stimuli are shown in Figure 5.1. With an exposure duration of 4 s, eleven sound stimuli were generated with SELs from 61 to 91 dBA in 3-dB steps (International Organization for Standardization, 2003a), and ten vibration stimuli were generated with VDV from 0.11 to 1.10 $\text{ms}^{-1.75}$ in $0.11\text{-}\text{ms}^{-1.75}$ steps (British Standards Institution, 1987; International Organization for Standardization, 1997). For the 4-s stimuli used in the current study, the ratio of the SPL to the SEL was 6 dB, and the ratio of the r.m.s. acceleration to the VDV was $0.51 (\text{ms}^{-2} / \text{ms}^{-1.75})$.

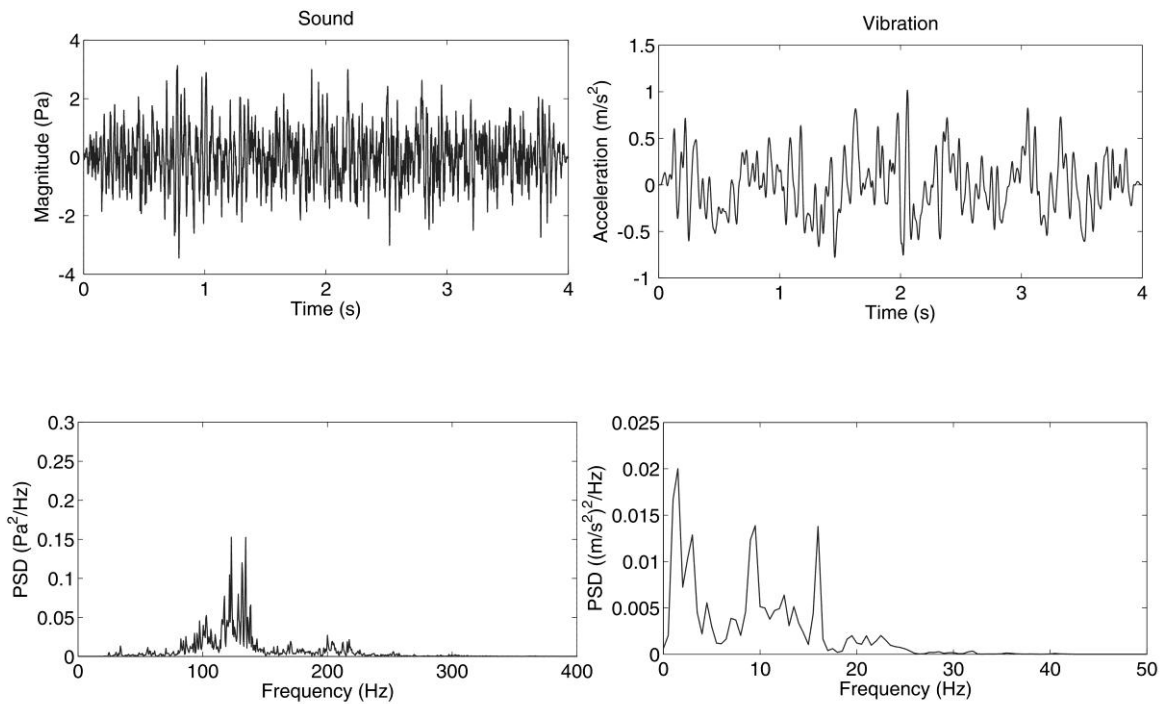


Figure 5.1 The time series and frequency spectrum of sound (A-weighted) and vibration stimuli (W_b weighted)

5.2.3 Procedure

Subjective judgements of ‘discomfort’ were obtained using the method of relative magnitude estimation (RME). The experiment was implemented in two sessions in a balanced and random order. In session A, each subject was presented with all possible 110 combinations of eleven levels of noise with ten magnitudes of vibration in a different random order. After each presentation, the subjects were asked to state the discomfort caused by the noise, assuming the discomfort caused by the vibration was 100. In session B, each subject was presented with ten combinations of all ten magnitudes of vibration combined with the 76 dBA SEL noise stimulus in a different random order. After each presentation, the subjects were asked to state the discomfort caused by the vibration, assuming the discomfort caused by the noise was 100.

Before commencing the experiment, subjects were provided with written instructions (Appendix A2) and then practiced judging the lengths of lines drawn on paper and then some combined noise and vibration stimuli until they felt confident with magnitude estimation.

5.3 Results

5.3.1 Discomfort of noise relative to reference vibrations

Median subjective ratings of the discomfort associated with the eleven levels of noise (as a function of L_{AE}) relative to ten magnitudes of vibration during the simultaneous presentation of noise and vibration are shown in Table 5.1, assuming the discomfort of the different vibration references was always 100.

Linear regression analyses were performed between the median values of the dependent variable, $\log_{10}(\psi_s)$, and the independent variable, L_{AE} , for each vibration stimulus. The intercepts, the slopes, and the correlation coefficients are shown in Table 5.2. From the linear relationships, the SELs that would produce the same discomfort as each vibration magnitude were obtained

Table 5.1 The median magnitude estimates of discomfort produced by noise relative to discomfort produced by vibration for 12 subjects

$a_{VDV} (ms^{-1.75})$											
L_{AE} (dBA)		V_1 0.11	V_2 0.22	V_3 0.33	V_4 0.44	V_5 0.55	V_6 0.66	V_7 0.77	V_8 0.88	V_9 0.99	V_{10} 1.10
	N_1 61	90	73	45	35	35	28	28	23	28	10
	N_2 64	95	80	55	45	50	40	30	40	20	28
	N_3 67	100	85	78	45	60	55	50	55	45	35
	N_4 70	140	103	80	85	73	60	60	55	60	50
	N_5 73	125	120	83	93	90	70	73	80	73	65
	N_6 76	155	110	115	100	100	85	95	80	80	78
	N_7 79	200	145	120	115	120	105	105	100	95	100
	N_8 82	190	150	143	128	123	100	125	105	115	100
	N_9 85	225	190	163	170	150	150	150	150	125	125
	N_{10} 88	300	235	225	200	190	175	200	200	180	175
	N_{11} 91	325	300	250	225	225	225	250	250	200	190

Table 5.2 The linear regression analysis showing the L_{AE} equivalent to each a_{VDV} .

a_{VDV} ($\text{ms}^{-1.75}$)	Slope ($n_s/20$)	Intercept ($\log_{10}(k_s)$) (dB)	Correlation (r_s^2)	L_{AE} (dBA)
0.11	0.019	0.754	0.962	65.6
0.22	0.019	0.644	0.956	71.4
0.33	0.024	0.238	0.979	73.4
0.44	0.027	-0.047	0.962	75.8
0.55	0.025	0.110	0.981	75.6
0.66	0.027	-0.155	0.977	79.8
0.77	0.031	-0.436	0.985	78.6
0.88	0.030	-0.367	0.963	78.9
0.99	0.031	-0.499	0.934	79.0
1.10	0.036	-0.950	0.914	81.9

and are shown as the L_{AE} column in Table 5.2.

From Equation (5.1), after linear regression between the SELs and VDV in Table 5.2, the relationship for the subjective equality of discomfort between noise and vibration was obtained, with a correlation coefficient of 0.958:

$$L_{AE} = 80.4 + 14.7 \log_{10}(a_{VDV}). \quad (5.2)$$

5.3.2 Discomfort of vibration relative to a reference noise

Median subjective ratings of the discomfort associated with the 10 magnitudes of vibration (as a function of a_{VDV}) relative to the 76 dBA SEL noise stimulus during the simultaneous presentation of noise and vibration are shown in Table 5.3. Linear regression analyses between the median values of the dependent variable, $\log_{10}(\psi_v)$, and the independent variable, $\log_{10}(a_{VDV})$, produced the intercept, slope, and correlation coefficient shown in Table 5.3.

5.3.3 Derivation of subjective equivalence between noise and vibration

Calculated from the regression parameters in Table 5.3, (i.e., intercept, $\log_{10}(k_v)$, and slope, n_v) $0.58 \text{ ms}^{-1.75}$ VDV would produce the same discomfort (i.e., $\log_{10}(\psi_v) = 100$) as 76 dBA SEL. The subjective equivalence equation could be determined by employing the L_{AE} and the a_{VDV} values in Table 5.2 together with the $0.58 \text{ ms}^{-1.75}$ VDV and 76 dBA SEL.

For example, from Table 5.2, the 78.6 dBA SEL would produce the same discomfort as the $0.78 \text{ ms}^{-1.75}$ VDV, together with 76 dBA SEL and the $0.58 \text{ ms}^{-1.75}$ VDV, the subjective equivalence equation in terms of L_{AE} and $\log_{10}(a_{VDV})$ was obtained:

$$L_{AE} = 80.8 + 20.2 \log_{10}(a_{VDV}). \quad (5.3)$$

Different linear relationships for the subjective equality of discomfort caused by noise and vibration are listed in Table 5.4. The slope and intercept in each row of Table 5.4 were calculated by linear regression of $0.58 \text{ ms}^{-1.75}$ VDV and the 76 dBA SEL together with the corresponding VDV and SELs in the same row of Table 5.4. Different from the values of slope

(i.e., $20(n_v/n_s)$) in Table 5.4, values from 19.6 to 37.2 could be calculated by employing the values of $n_s/20$ from 0.019 to 0.036 in Table 5.2 together with the value of n_v (i.e., 0.706).

5.4 Discussion

5.4.1 Equivalence between sound and vibration in different studies

Several previous studies have produced information on the subjective equivalence of sound and vibration. In a study of the subjective equivalence of 1-kHz pure tones (SPLs from 65 to 100 dBA) and 10-Hz sinusoidal whole-body vertical vibration (at 0.20, 0.30, 0.40, 0.50, 0.60, 0.80, 1.00, and 1.20 ms^{-2} r.m.s.) subjects were presented with the noise and the vibration simultaneously and asked to say which of the two stimuli they would prefer to reduce (Fleming and Griffin, 1975). The L_{AE} and a_{VDV} values can be calculated from the L_{Aeq} and the r.m.s. acceleration to provide the relation:

Table 5.3 Median magnitude estimates of vibration discomfort (where $L_{AE} = 76\text{dBA}$ causes a magnitude estimate of discomfort of 100) for 12 subjects and linear regression.

$a_{VDV} (\text{ms}^{-1.75})$	Discomfort	Regression parameters
0.11	30	Intercept: $\log_{10}(k_v) = 2.165$
0.22	50	
0.33	70	
0.44	80	Slope: $n_v = 0.706$
0.55	100	
0.66	110	
0.77	128	Correlation: $r^2 = 0.996$
0.88	130	
0.99	145	
1.10	155	

Table 5.4 Linear relationships for subjective equality of the discomfort caused by noise and the discomfort caused by vibration.

$a_{VDV} (\text{ms}^{-1.75})$	$L_{AE} (\text{dBA})$	Slope ($20n_v/n_s$)	Intercept (k) (dB)
0.11	65.6	14.4	79.4
0.22	71.4	10.9	78.6
0.33	73.4	10.4	78.4
0.44	75.8	1.55	76.4
0.55	75.6	26.2	82.2
0.66	79.8	71.6	92.7
0.77	78.6	20.2	80.8
0.88	78.9	15.6	79.7
0.99	79.0	12.7	79.0
1.10	81.9	20.6	80.9

$$L_{AE} = 93.6 + 33.0 \log_{10}(a_{VDV}). \quad (5.4)$$

Using sequential presentations of 2.5-s stimuli, Hempstock and Saunders (1976) asked subjects to adjust the level of noise (300-Hz bandwidth random noise centred on 2000 Hz) to be subjectively equivalent to various magnitudes of sinusoidal vibration (5, 10, 20, 30, 40, and 80 Hz presented at 0.5, 1.0, 2.0, 4.0, and 6.0 ms⁻² r.m.s.), and to adjust the magnitude of vibration to be subjectively equivalent to various levels of noise. Using the median slopes and intercepts, further analysis provides the following relations between the a_{VDV} and the L_{AE} :

$$L_{AE} = 81.8 + 21.3 \log_{10}(a_{VDV}), \quad (5.5)$$

when the vibration was the independent variable, and

$$L_{AE} = 77.9 + 43.5 \log_{10}(a_{VDV}), \quad (5.6)$$

when the noise was the independent variable.

Using simultaneous presentations of broad-band noise (L_{Aeq} from 15 dB to 115 dB) and whole-body vertical vibration recorded in the forklift trucks (0.95, 1.1, 1.4, and 2.0 ms⁻² r.m.s. at resonance frequency 3.1-Hz, and 1.3, 1.6, 2.4 and 3.5 ms⁻² r.m.s. at resonance frequency 6.3-Hz) recorded in forklift trucks, Kjellberg *et al.* (1985) asked subjects to adjust the noise to a level that gave the same discomfort as the vibration. The subjective equivalence of noise and vibration can be obtained from their results and expressed as:

$$L_{AE} = 75.5 + 40.0 \log_{10}(a_{VDV}). \quad (5.7)$$

Howarth and Griffin (1990b) employed a method similar to Fleming and Griffin (1975), but with simultaneous simulations of the noise and vertical vibration recorded over 24 s in a building adjacent to a railway during the passage of a train. With L_{AE} in the range 59 to 84 dBA and a_{VDV} in the range 0.07 to 0.40 ms^{-1.75} (W_b weighted), the subjective equality between the stimuli was expressed by:

$$L_{AE} = 89.2 + 29.3 \log_{10}(a_{VDV}). \quad (5.8)$$

The annoyance caused by reproductions of the noise and vibration in a flat produced by a passing tram was studied by Paulsen and Kastka (1995). With the r.m.s. velocity of vibration in the range 0.03 to 0.4 mm/s and the SPL of noise in the range 28 to 61 dBA, equivalence between the simultaneous noise and vibration was given by:

$$L_{AE} = 51.9 + 14.4 \log_{10}(v_m). \quad (5.9)$$

The subjective equivalence between noise and vibration implied by the findings of previous studies are compared with the relationship found from session A (with noise discomfort relative to vibration) of present study in Figure 5.2. The equivalence between noise and vibration is illustrated for the range of VDV (of r.m.s. velocity for Paulsen and Kastka's contour) employed in the experiment.

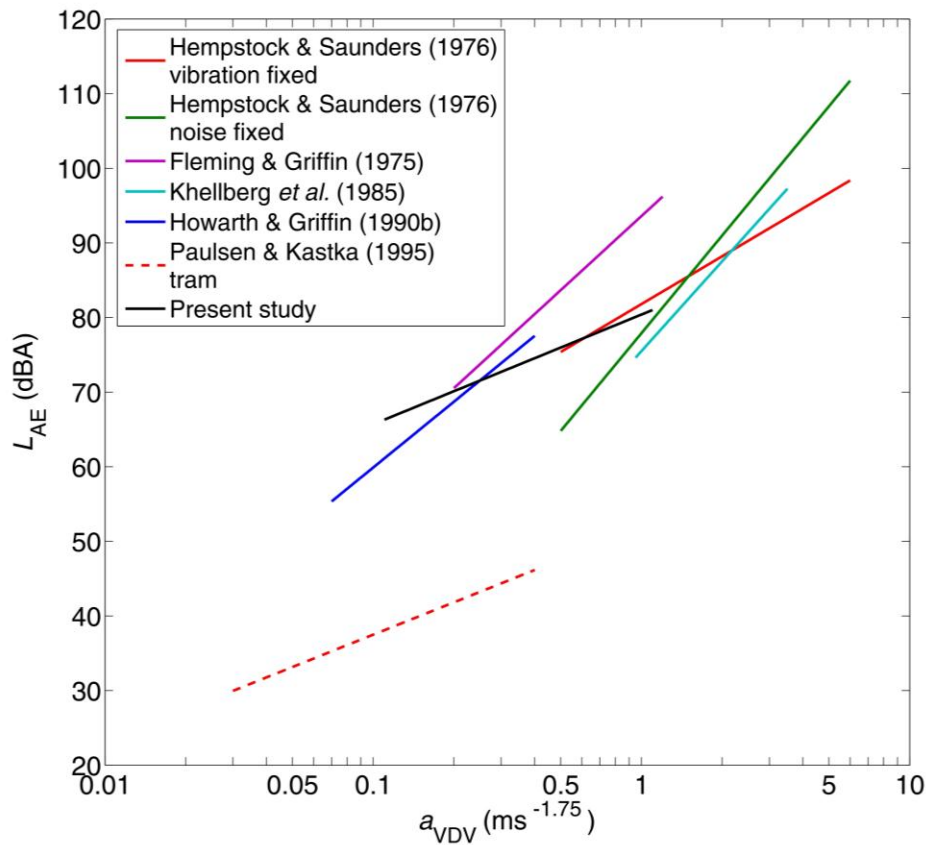


Figure 5.2 Comparison of the subjective equivalence contours from the present study and the previous studies.

Howarth and Griffin (1990) used the same method as Fleming and Griffin (1975) and obtained a similar slope, even though Fleming and Griffin used sinusoidal sound and vibration and Howarth and Griffin used field measurements of railway-induced building vibration and noise. Kjellberg *et al.* (1985) used a similar method to Hempstock and Saunders (1975), but the slope of the equivalence contour is almost twice that of Hempstock and Saunders obtained by matching noise to fixed vibration, and greater than those of all other studies. The findings of Paulsen and Kastka (1995) correspond to a slope only half that found by Howarth and Griffin (1990). The difference might be associated with the lower levels of the sound stimuli that were recorded in field measurements in a building near passing trams. The slope obtained in session A (with noise discomfort relative to vibration) of the present study with noise and vibration in a car is similar to that obtained by Paulsen and Kastka, but the intercepts from the two studies differ, possibly due to the lower levels of sound stimuli and lower level background noise but the similar vibration values in the Paulsen and Kastka study. The findings from the present study fit with results presented by Hempstock and Saunders when the vibration was the independent variable.

5.4.2 Influence of vibration on the discomfort of noise

From Stevens' power law (Section 2.3.2), the relation between the dependent variable, ψ_s , and the independent variable, L_{AE} , can be written as:

$$\log_{10}(\psi_s) = \log_{10}(k_s) + n_s/20 L_{AE} \quad (5.10)$$

As shown in Table 5.2, when the magnitude of the vibration reference increased from 0.11 to 1.12 $\text{ms}^{-1.75}$, the slope, $n_s/20$, increased from 0.019 to 0.036, whereas Stevens suggested the slope would be approximately 0.033 (Stevens, 1986). One possible reason for the increase in slope might be that when subjects are exposed to simultaneous noise and vibration there is a 'masking effect', with higher vibration magnitudes masking lower levels of noise, so subjects are less sensitive to lower levels of noise and tend to give lower discomfort ratings, whereas the higher levels of noise are less masked. This would result in discomfort ratings for sound stimuli presented simultaneously with higher magnitude vibration stimuli increasing at a greater rate than those presented simultaneously with lower magnitude vibration stimuli. Therefore, in the L_{AE} column in Table 5.2, the L_{AE} values producing the same discomfort as each vibration magnitude would be underestimated when the magnitude of the vibration stimulus increases, which might also be the reason of a low slope in present study. If this explanation is verified, it may be necessary to incorporate masking effects in the prediction of the relative or combined importance of simultaneous noise and vibration in vehicles.

In session B of present study (with vibration discomfort relative to noise), the exponent, $n_v = 0.706$ is consistent to the average exponent value 0.71 found by Morioka and Griffin (2006) who investigated whole-body vertical sinusoidal vibration at frequencies between 2 to 50 Hz. In Morioka and Griffin's study (2006), subjects were exposed to the 77 dBA SEL white noise when judging 2-s vibration stimuli; while in present study, subjects were exposed to the 76 dBA SEL low frequency noise when judging 4-s vibration stimuli. If the noise has a 'masking effect' on the judgements of vibration, it is expected that the results of discomfort of vibration in these two studies are consistent since the subjects were exposed to the sound having similar levels.

The slopes, $20(n_v/n_s)$, in the equivalence comfort contours varied much when calculated by employing different exponents, n_s , from session A (with noise discomfort relative to vibration), and the exponents, n_v , 0.0706 from session B (with vibration discomfort relative to noise). It might not be appropriate to determine the $20(n_v/n_s)$, by using n_v or n_s from unrelated experiments.

5.5 Conclusion

Contours for the equivalence of comfort between noise and vibration in cars may be approximately described by $L_{AE} = 80.4 + 14.7 \log_{10}(a_{VDV})$. However, it seems likely that there are other factors that influence the equivalence between noise and vibration and that an understanding of these factors may be necessary for a general method of predicting the equivalence between noise and vibration.

Chapter 6 Effect of physical magnitudes on the relative discomfort of noise and vibration II

6.1 Introduction

The study in this chapter continues the determination of the subjective equivalence of noise and vibration by recognising that the subjective equivalence may depend on: (i) the level of the noise and the magnitude of the vibration, (ii) whether noise was judged relative to vibration or vibration was judged relative to noise, and (iii) whether the noise and vibration were presented simultaneously or sequentially. The study was primarily designed to test three hypotheses: (i) the subjective equivalence between noise and vibration (e.g., $L_{AE} = k + 20(n_v/n_s)\log_{10}(a_{VDV})$), would differ depending on whether noise is judged relative to vibration or vibration is judged relative to noise, (ii) the slope, $s = 20(n_v/n_s)$, would depend on both the level of noise (because high magnitudes of vibration may influence judgements of low levels of noise) and the magnitude of vibration (because high levels of noise may influence judgements of low magnitudes of vibration), and (iii) the influence of noise on judgements of vibration, and the influence of vibration on judgements of noise, would be less when noise and vibration are presented sequentially than when they are presented simultaneously.

6.2 Method

6.2.1 Subjects

Twenty subjects (10 male and 10 female), with median age 23 years (range 19 to 30 years), stature 169 cm (range 162 to 196 cm), and weight 60 kg (range 46 to 110 kg) volunteered to take part in the experiment. The subjects were students or staff of the University of Southampton.

6.2.2 Stimuli

The vibration and sound stimuli used in the experiment were developed from the same sample as in the last experiment (see Section 5.2.2) by applying a cosine taper to the first and last 0.2 s. With an exposure duration of 4 s, seven sound stimuli were generated with SELs from 70 to 88 dBA in 3 dB steps (International Organization for Standardization, 2003a), and seven vibration stimuli were generated with VDV_s of 0.092, 0.146, 0.231, 0.366, 0.581, 0.92 and 1.458 ms^{-1.75} (British Standards Institution, 1987; International Organization for Standardization, 1997). For the 4-s stimuli used in the current study, the ratio of the SPL to the SEL was 6 dB, and the ratio of the r.m.s. acceleration to the VDV was 0.51 (ms⁻²/ms^{-1.75}).

6.2.3 Procedure

Judgments of 'discomfort' were obtained using the method of relative magnitude estimation (RME). The sound and vibration stimuli were presented in pairs with one of the two stimuli identified as the reference stimulus. Before commencing the experiment, subjects were

provided with written instructions (Appendix A3) and practiced judging some combined noise and vibration stimuli until they felt confident with magnitude estimation.

The experiment was undertaken in four sessions. In session A, subjects were presented with all 49 possible combinations of the seven levels of noise and the seven magnitudes of vibration. The pairs of stimuli (i.e., sound and vibration) were presented simultaneously in an independent random order. For each presentation, the subjects were asked to state the discomfort caused by the noise, assuming the discomfort caused by the reference vibration was 100. Session B was similar to session A, except the subjects were asked to state the discomfort caused by the vibration, assuming the discomfort caused by the reference noise was 100. Session C was similar to session A, except the vibration was presented prior to the noise and subjects judged the discomfort caused by the noise assuming the discomfort caused by the reference vibration was 100. Session D was similar to session C, except the noise was presented prior to the vibration and subjects judged the discomfort caused by the vibration assuming the discomfort caused by the reference noise was 100. Subjects experienced the four sessions on different days and in a balanced order. When presenting the noise and vibration sequentially (in sessions C and D), the stimuli were separated by a 1-s pause, and each pair of noise and vibration stimuli was presented twice (e.g., noise-vibration-noise-vibration) before obtaining a response so as to minimise any order effect (Davidson and Beaver, 1977).

6.3 Results

6.3.1 Discomfort of noise judged relative to simultaneous or sequential reference vibration

Median subjective magnitudes of the discomfort associated with the seven levels of noise (as a function of L_{AE}) relative to the seven magnitudes of vibration during the simultaneous and sequential presentations of noise and vibration are shown in Tables 6.1 and 6.2, respectively, where the subjective magnitude of the discomfort associated with each of the reference magnitudes of vibration is always 100.

Linear regression analyses were performed between the median values of the dependent variable, $\log_{10}(\psi_s)$, and the independent variable, L_{AE} , for each vibration stimulus. The intercepts, the slopes, and the correlation coefficients are shown in Tables 6.1 and 6.2. From the linear relationships, the SPLs that produced the same discomfort as each reference vibration magnitude (i.e. a subjective magnitude of 100) were obtained and are shown as the L_{AE1} and L_{AE2} columns in Tables 6.1 and 6.2, respectively.

From Equation (5.1), linear regression between the L_{AE1} and a_{VDV} values in Table 6.1, gave the relationship for subjective equality of discomfort between simultaneous noise and vibration:

$$L_{AE} = 82.1 + 13.0 \log_{10}(a_{VDV}). \quad (6.1)$$

Linear regression between the L_{AE2} and a_{VDV} values in Table 6.2 gave the relationship for subjective equality of discomfort between sequential noise and vibration:

$$L_{AE} = 79.8 + 12.4 \log_{10}(a_{VDV}). \quad (6.2)$$

The same procedures applied to the magnitude estimates provided by each subject showed no difference in the slopes, s , between simultaneous and sequential presentation ($p = 0.145$ Wilcoxon), but a significant increase in the intercepts k with simultaneous presentation ($p = 0.007$ Wilcoxon).

6.3.2 Discomfort of vibration judged relative to simultaneous or sequential reference noise

Median subjective magnitudes of the discomfort associated with the seven magnitudes of vibration (as a function of a_{VDV}) relative to the seven levels of noise during the simultaneous and sequential presentation of noise and vibration are shown in Tables 6.3 and 6.4, respectively, where the subjective magnitude of the discomfort associated with each of the reference levels of noise is always 100.

Linear regression analyses were performed between the median values of the dependent variable, $\log_{10}(\psi_v)$, and the independent variable, a_{VDV} , for each noise stimulus. The intercepts, the slopes, and the correlation coefficients are shown in Tables 6.3 and 6.4. From the linear relationships, the vibration dose values that produced the same discomfort as each reference noise level (i.e. a subjective magnitude of 100) were obtained and are shown as the a_{VDV1} and a_{VDV2} columns in Tables 6.3 and 6.4, respectively.

From Equation (5.1), linear regression between the L_{AE} and a_{VDV1} values in Table 6.3, gave the relationship for the subjective equality of discomfort between simultaneous noise and vibration:

$$L_{AE} = 84.8 + 30.4 \log_{10}(a_{VDV}). \quad (6.3)$$

Linear regression between the L_{AE} and a_{VDV2} values in Table 6.4 gave the relationship for subjective equality of discomfort between sequential noise and vibration:

$$L_{AE} = 84.4 + 32.6 \log_{10}(a_{VDV}). \quad (6.4)$$

The same procedure applied to the magnitude estimates provided by each subject showed no difference in the slopes, s , or the intercepts, k , between simultaneous and sequential presentation (slope: $p = 0.478$; intercept: $p = 0.351$; Wilcoxon).

Table 6.1 Magnitude estimates for the discomfort of noise relative to the discomfort of simultaneous vibration, and linear regression analysis showing the sound exposure level, L_{AE1} , equivalent to each reference vibration dose value, a_{VDV} . Medians of 20 subjects.

$a_{VDV} (ms^{-1.75})$								
L_{AE} (dBA)		V ₁ 0.092	V ₂ 0.146	V ₃ 0.231	V ₄ 0.366	V ₅ 0.581	V ₆ 0.920	V ₇ 1.458
	N1 70	115	100	100	85	70	45	35
	N2 73	120	102.5	100	95	77.5	50	50
	N3 76	127.5	120	100	95	92.5	75	60
	N4 79	165	140	120	110	100	85	80
	N5 82	200	180	150	135	110	90	85
	N6 85	250	200	200	175	150	117.5	100
	N7 88	250	250	200	200	185	150	110
$a_{VDV} (ms^{-1.75})$	Slope ($n_{s1}/20$)	Intercept ($\log_{10}(k_{s1})$) (dB)				Correlation (r_{s1}^2)		L_{AE1} (dBA)
0.092	0.022	0.488				0.974		68.7
0.146	0.023	0.336				0.987		72.4
0.232	0.020	0.541				0.943		73.0
0.366	0.021	0.395				0.970		76.4
0.579	0.023	0.225				0.979		77.2
0.920	0.028	-0.340				0.985		83.6
1.457	0.027	-0.269				0.975		84.0

Equivalent continuous SPL, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

Table 6.2 Magnitude estimates for the discomfort of noise relative to the discomfort of sequential vibration, and linear regression analysis showing the sound exposure level, L_{AE2} , equivalent to each reference vibration dose value, a_{VDV} . Medians of 20 subjects.

$a_{VDV} (ms^{-1.75})$								
L_{AE} (dBA)		V ₁ 0.092	V ₂ 0.146	V ₃ 0.231	V ₄ 0.366	V ₅ 0.581	V ₆ 0.920	V ₇ 1.458
	N1 70	120	100	100	97.5	75	70	50
	N2 73	130	120	100	90	80	75	50
	N3 76	145	147.5	122.5	110	95	80	75
	N4 79	175	140	117.5	132.5	110	97.5	87.5
	N5 82	200	200	160	145	125	110	107.5
	N6 85	200	200	200	180	140	125	112.5
	N7 88	275	250	215	200	200	172.5	120
$a_{VDV} (ms^{-1.75})$	Slope ($n_{s2}/20$)	Intercept ($\log_{10}(k_{s2})$) (dB)				Correlation (r_{s2}^2)		L_{AE2} (dBA)
0.092	0.019	0.735				0.978		66.6
0.146	0.021	0.535				0.973		69.8
0.232	0.020	0.529				0.961		73.6
0.366	0.020	0.558				0.974		72.1
0.579	0.022	0.278				0.980		78.3
0.920	0.021	0.346				0.974		78.8
1.457	0.024	0.029				0.962		82.1

Equivalent continuous SPL, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

Table 6.3 Magnitude estimates for the discomfort of vibration relative to the discomfort of simultaneous noise, and linear regression analysis showing the vibration dose value, a_{VDV1} , equivalent to each reference noise exposure level, L_{AE} . Medians of 20 subjects.

$a_{VDV} (ms^{-1.75})$								
L_{AE} (dBA)		V ₁ 0.092	V ₂ 0.146	V ₃ 0.231	V ₄ 0.366	V ₅ 0.581	V ₆ 0.920	V ₇ 1.458
	N1 70	50	75	100	100	120	150	177.5
	N2 73	50	65	100	100	120	140	155
	N3 76	40	60	82.5	90	100	130	150
	N4 79	30	40	50	85	100	120	150
	N5 82	17.5	30	50	72.5	95	100	137.5
	N6 85	17.5	20	27.5	50	65	97.5	120
	N7 88	10	10	22.5	30	55	80	100
L_{AE} (dBA)	Slope (n_{v1})		Intercept ($\log_{10}(k_{v1})$)			Correlation (r_{v1}^2)		a_{VDV1} ($ms^{-1.75}$)
70	0.417		2.193			0.974		0.344
73	0.397		2.163			0.966		0.388
76	0.443		2.128			0.975		0.514
79	0.599		2.113			0.988		0.647
82	0.717		2.083			0.972		0.766
85	0.761		1.984			0.990		1.050
88	0.928		1.901			0.985		1.279

Equivalent continuous SPL, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

Table 6.4 Magnitude estimates for the discomfort of vibration relative to the discomfort of sequential noise, and linear regression analysis showing the vibration dose value, a_{VDV2} , equivalent to each reference noise exposure level, L_{AE} . Medians of 20 subjects.

$a_{VDV} (ms^{-1.75})$								
L_{AE} (dBA)		V ₁ 0.092	V ₂ 0.146	V ₃ 0.231	V ₄ 0.366	V ₅ 0.581	V ₆ 0.920	V ₇ 1.458
	N1 70	47.5	80	90	100	112.5	150	190
	N2 73	30	50	80	100	117.5	130	177.5
	N3 76	30	42.5	70	95	105	120	150
	N4 79	20	30	65	80	100	120	150
	N5 82	17.5	30	50	60	90	100	150
	N6 85	20	20	20	45	75	100	102.5
	N7 88	10	20	22.5	35	60	85	100
L_{AE} (dBA)	Slope (n_{v2})		Intercept ($\log_{10}(k_{v2})$)			Correlation (r_{v2}^2)		a_{VDV2} ($ms^{-1.75}$)
70	0.438		2.197			0.971		0.355
73	0.592		2.189			0.967		0.480
76	0.567		2.134			0.969		0.578
79	0.718		2.134			0.964		0.650
82	0.733		2.081			0.984		0.774
85	0.733		1.954			0.948		1.156
88	0.837		1.923			0.988		1.236

Equivalent continuous SPL, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

6.3.3 Contours of equivalence between sound and vibration

Contours showing the noise and vibration that produced equivalent discomfort in the four sessions are shown in Figure 6.1 and compared in Figure 6.2.

The slopes, s , were significantly greater when judging vibration relative to noise than when judging noise relative to vibration ($p = 0.015$ for simultaneous stimuli, $p = 0.001$ for sequential stimuli, Wilcoxon). Similarly, the intercepts, k , were significantly greater when judging vibration relative to noise than when judging noise relative to vibration ($p = 0.011$ for simultaneous stimuli, $p = 0.002$ for sequential stimuli, Wilcoxon).

6.4 Discussion

6.4.1 Equivalence between sound and vibration in different studies

The subjective equivalence between noise and vibration implied by the findings of previous studies of Fleming and Griffin (1975), Hempstock and Saunders (1976), Kjellberg *et al.* (1985), Howarth and Griffin (1990b), Paulsen and Kastka (1995), and last chapter (see Section 5.4.1) are compared with the four contours from the present study in Figure 6.3. The equivalence between noise and vibration is illustrated for the range of VDV (of r.m.s. velocity for Paulsen and Kastka's contour) employed in the experiment.

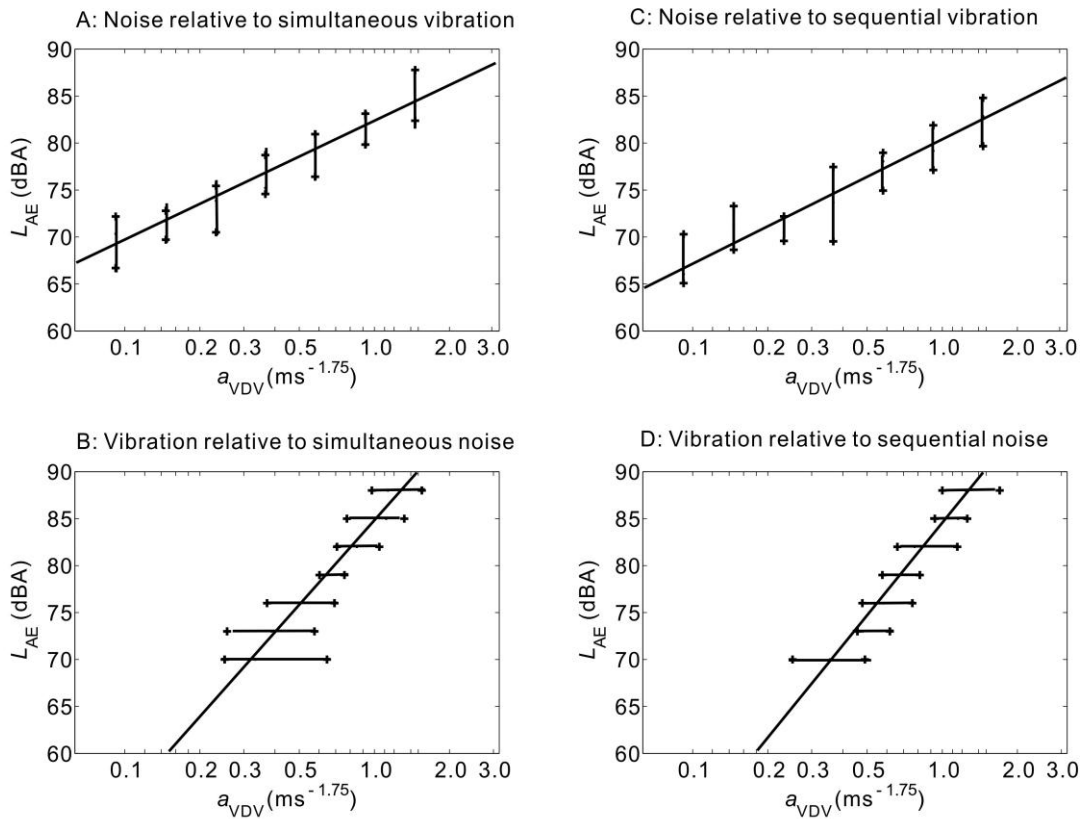


Figure 6.1 The subjective equivalence between noise and vibration in the different sessions of the study. Medians and inter-quartiles ranges of individual data from 20 subjects.

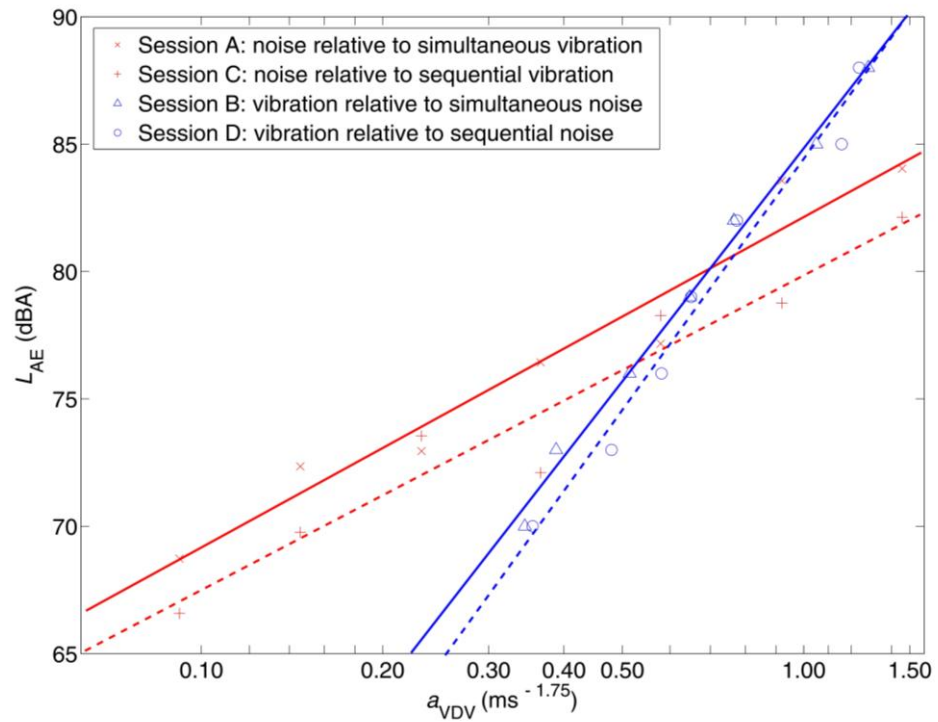


Figure 6.2 Subjective equivalence between noise and vibration in the different sessions of the study. Medians from 20 subjects.

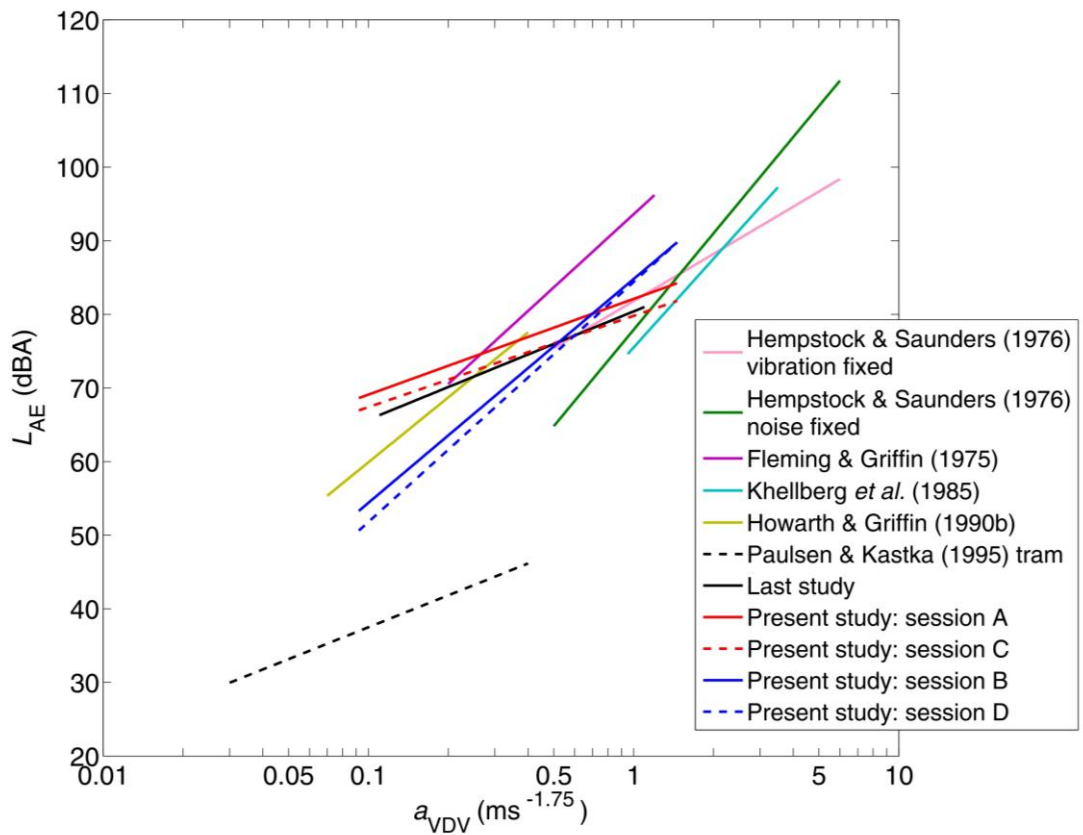


Figure 6.3 Comparison of equivalence contours from the present study and previous studies.

The slopes of the equivalent comfort contours obtained in sessions A and C of the present study (i.e., 13.0 and 12.4), when judging the discomfort of noise relative to either simultaneous or sequential vibration (Equations (6.1) and (6.2)), may seem reasonably consistent with the slopes of 21.3 obtained by Hempstock and Saunders (1976) with fixed vibration and 14.7 obtained in the last experiment. Although the slope of 14.4 obtained by Paulsen and Kastka (1995) is also similar, the intercept differs, possibly due to their subjects judging much lower levels of sound relative to similar magnitudes of vibration. It has been reported that irrelevant noises (e.g., sinusoidal noise or white noise) are evaluated louder than real noises (e.g., Suzuki *et al.*, 2006), suggesting the intercepts may be greater when using artificial stimuli than when using real stimuli, consistent with Howarth and Griffin (1990b) finding a slightly lower intercept than Fleming and Griffin (1975) even though they used the same method.

The slopes of equivalent comfort contours obtained in sessions B and D of the present study (i.e., 30.4 and 32.6), when judging the discomfort of vibration relative to simultaneous or sequential noise (Equations (6.3) and (6.4)), are reasonably consistent with the slope of 33.0 obtained by Fleming and Griffin (1975), the slope of 40 obtained by Kjellberg *et al.* (1985), and the slope of 29.3 obtained by Howarth and Griffin (1990b).

Some of the differences between the equivalent comfort contours might be explained by the 'range effect' (Poulton, 1968, 1973; Stevens, 1968). Hempstock and Saunders (1975) employed the same noise levels as Fleming and Griffin (i.e., 65 to 100 dBA) but a wider range of vibration magnitudes in the vibration fixed session (0.5 to 6.0 ms^{-2} r.m.s compared with 0.2 to 1.2 ms^{-2} r.m.s.), consistent with them finding a lower slope (i.e., 21.3 compared with 33.0). Paulsen and Kastka employed lower levels of sound than others and found a lower slope, also consistent with the range effect. It might also be significant that Kjellberg *et al.* (1985) used a wide range of sound levels (15 to 115 dB) and greater vibration magnitudes (0.95 to 3.5 ms^{-2} r.m.s.), and obtained a greater slope, also consistent with a range effect.

In the present study, the slopes of the equivalent comfort contours obtained when judging noise relative to vibration (13.0 and 12.4 in sessions A and C, respectively), are much less than when judging vibration relative to noise (30.4 and 32.6 in sessions B and D, respectively), yet both could be considered consistent with the findings of previous studies. The difference in slopes may be associated with whether subjects focus on the noise or focus on the vibration (i.e. whether the noise or vibration is dominant). Paulsen and Kastka (1995) asked subjects to "indicate on a scale from 0 to 9 how strong the perceived noise was", so the noise level was the dominant modality, as in the last study, and in sessions A and C of the present study, where similar slopes were obtained. In the Hempstock and Saunders (1976) study, when the subjects were asked to adjust the noise level to be equivalent to a fixed magnitude of vibration, the median slope was 21.3, broadly consistent with other studies where the discomfort caused by the noise was the principal dependent variable.

Paulsen and Kastka found that the slope obtained for the modality 'noise' was independent of the question (e.g., asking for the 'noise' or the 'overall situation'), whereas the evaluation of the

modality 'vibration' was dependent on how the question was expressed to the subjects (Paulsen and Kastka, 1995). When being asked to evaluate noise, subjects may be more likely to focus on the modality 'noise', whereas when they are asked to evaluate vibration, or not told which modality (i.e. noise, or vibration) to evaluate, subjects may focus on the more unusual modality of 'vibration'. In sessions B and D of the present study, subjects judged the discomfort of vibration relative to simultaneous or sequential noise, and the principal dependent variable (i.e., discomfort caused by vibration) may have been the dominant modality. When the discomfort caused by vibration was the dependent variable, Hempstock and Saunders (1976) found an average slope of 43.5 within the range 37.0 to 47.6, consistent with the results of sessions B and D of the present study.

Both Fleming and Griffin (1975) and Howarth and Griffin (1990b) asked subjects to state whether they would prefer the vibration or the noise to be reduced, allowing either the vibration or the noise to be dominant, and they obtained similar slopes (33 and 29.3). Their slopes are similar to those obtained in the present study when judging the discomfort of vibration relative to noise (30.4 in session B and 32.6 in session D), suggesting their subjects may have focused more on the vibration than on the noise. Perhaps the vibration was less familiar to subjects and so demanded their attention.

Assuming $n_s = 0.68$ (Stevens, 1986), which was also assumed in the studies of Fleming and Griffin (1975) and Howarth and Griffin (1990b), and $n_v = 0.71$ (session B of the last study, see Section 5.3.2), a slope of about 21 can be obtained, similar to the average of the slopes of 13.0 and 12.4 from sessions A and C, and 30.4 and 32.6 from sessions B and D in present experiment. The value of 21 as the slope of the equivalence comfort contour may seem a sensible compromise for practical applications, but it will yield equivalence that differs from the experimental values when applied over a wide range of noise or vibration levels. An understanding for the reasons for the differing slopes would therefore appear to have both practical and academic value.

The slopes reported above are dependent on the durations of the stimuli, because the time-dependency used to express exposure to noise (i.e., SEL) differs from the time dependency used to express exposure to vibration (i.e., VDV). For example, if the findings of Howarth and Griffin (1990b) using 24-s stimuli are expressed in terms of SPL and r.m.s. acceleration, a slope of 25.1 is obtained compared to 29.3 when the findings are expressed in terms of SEL and VDV. For shorter durations, such as 10-s stimuli used by Fleming and Griffin (1975) and the 4-s stimuli used by Huang and Griffin (2010) and in present study, the differences in the slopes of equivalence comfort contours expressed by SPL and r.m.s. acceleration, or by SEL and VDV are relatively small. However, there remains uncertainty as to how much of the difference can be attributed to differences between the time-dependencies of noise and vibration because the VDV and the SEL may not be suitable indicators of the effect of duration on the equivalence between noise and vibration. The time-dependence of the subjective equivalence between noise and vibration appears to merit further consideration.

6.4.2 Influence of vibration on the discomfort of noise

From Stevens' power law for sound, $\psi_s = k_s \phi_s^{n_s}$, the relation between the dependent variable, ψ_s , and the independent variable, L_{AE} , can be written:

$$\log_{10}(\psi_s) = \log_{10}(k_s) + n_s/20 L_{AE}. \quad (6.5)$$

Linear regressions between the logarithm of the sound discomfort, ψ_s , and the sound level, L_{AE} , judged relative to the discomfort caused by each of the seven reference magnitudes of vibration are shown for simultaneous and sequential presentations in Figures 6.4 and 6.5, respectively. When the magnitude of the simultaneous reference vibration increased from 0.092 to 1.457 ms^{-1.75}, there was a trend for the median slope to increase from 0.022 to 0.028 ($p = 0.053$, Friedman; Table 6.1). When the reference vibration was presented sequentially, there was a non-significant increase in slope from 0.019 to 0.024 ($p = 0.226$, Friedman; Table 6.2).

If the discomfort caused by the noise was unaffected by the vibration, Figures 6.4 and 6.5 would show seven parallel lines differing due to the different levels of the reference noise. However, as the magnitude of the reference vibration increased, the slopes increased, so the difference in discomfort caused by the lowest and the highest magnitudes of vibration reduced as the level of the noise increased.

It seems reasonable to suppose that judgements provided by the subjects may have been influenced by a 'range effect' (Poulton, 1973) and a 'masking effect'. A range effect will tend to cause overestimation of the subjective magnitudes of very low magnitude stimuli and underestimation of the subjective magnitudes of very high magnitude stimuli. A masking effect would involve one stimulus reducing the subjective severity of the other stimulus.

It would appear that a masking effect could fully explain the findings: when subjects focused on the noise and gave numerical ratings of the discomfort caused by noise, the higher magnitudes of vibration may have masked their perceptions of the lower levels of noise (lower left of Figures 6.4 and 6.5). The masking effect reduced as the level of noise increased (moving to the right in Figures 6.4 and 6.5) and as the magnitude of the vibration reduced (moving up in Figures 6.4 and 6.5). Although there may have been a range effect it does not seem that a range effect can explain the findings: a range effect would tend to overestimate the subjective magnitudes of the low level noise stimuli in the lower left of Figures 6.4 and 6.5, yet they seem to be underestimated. Although a range effect might explain low values in the lower right of Figures 6.4 and 6.5, it does not seem plausible for these higher subjective magnitudes to be influenced by a range effect if the lower subjective magnitudes in the lower left of Figures 6.4 and 6.5 are not so influenced. Similar reasoning suggests it is unlikely an increase in ratings in the upper left of Figures 6.4 and 6.5, or a reduction in ratings in the upper right of Figures 6.4 and 6.5, could be fully explained by a range effect. It is tentatively concluded that although there may have been both a masking effect and a range effect, the masking effect was greater than the range effect, and that the findings might be fully explained by some form of 'masking' on noise by the

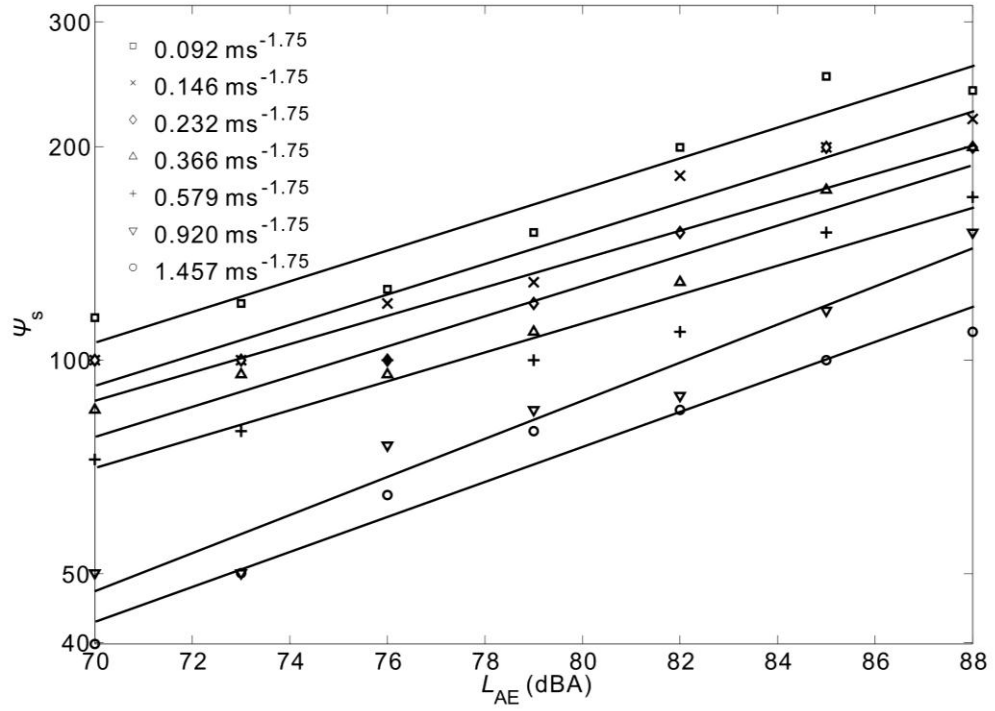


Figure 6.4 Linear regressions between the logarithm of the subjective magnitudes of noise discomfort and L_{AE1} when judged relative to 7 different magnitudes of simultaneous vibration. Medians from 20 subjects.

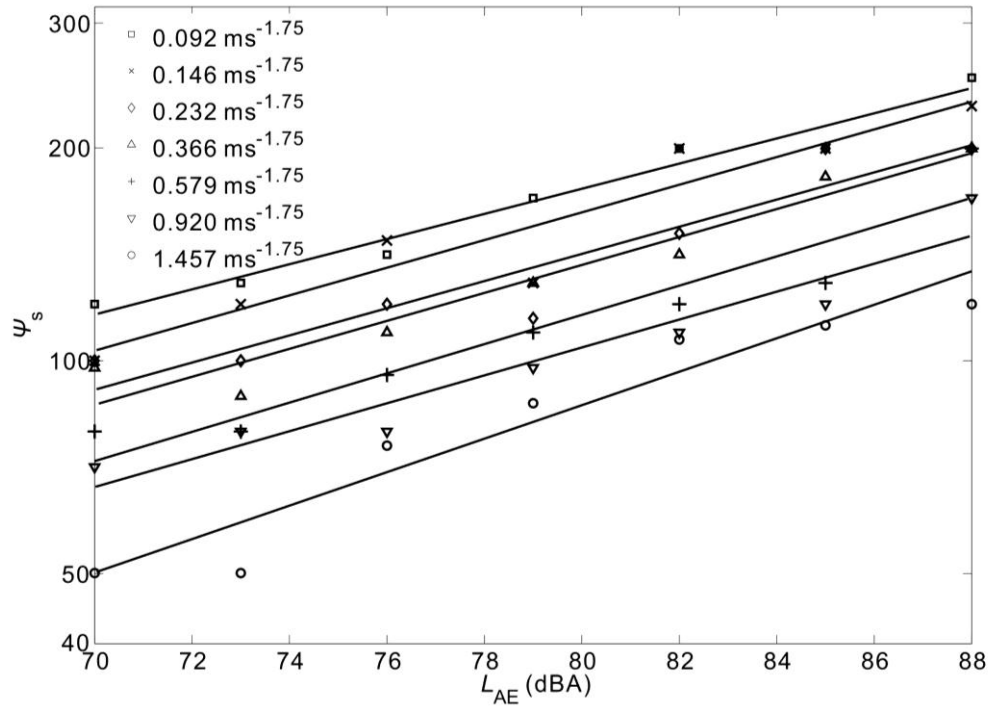


Figure 6.5 Linear regressions between the logarithm of the subjective magnitudes of noise discomfort and L_{AE2} when judged relative to 7 different magnitudes of sequential vibration. Medians from 20 subjects.

vibration.

It would be reasonable for any such masking to be less with sequential presentations of the noise and vibration, consistent with the significant increase in the intercept k with simultaneous presentation (see Section 6.3.1). This suggests the discomfort of noise is masked more by simultaneous vibration than by sequential vibration: with the same reference, higher levels of noise were needed to produce equivalent discomfort in session A than in session C (Tables 6.1 and 6.2).

The findings suggest it may be necessary to include a masking effect of vibration on judgements of noise discomfort in the prediction of the relative (and combined) importance of noise and vibration, irrespective of whether the vibration and noise are simultaneous or sequential.

6.4.3 Influence of noise on the discomfort of vibration

From $\psi_v = k_v \phi_v^{n_v}$, the relation between the dependent variable, ψ_v , and the independent variable, a_{VDV} , can be written as:

$$\log_{10}(\psi_v) = \log_{10}(k_v) + n_v \log_{10}(a_{VDV}) \quad (6.6)$$

From Tables 6.3 and 6.4, linear regressions between the logarithm of the vibration discomfort, ψ_v , and the vibration exposure, a_{VDV} , judged relative to the discomfort caused by each of the 7 reference levels of noise are shown for simultaneous and sequential presentations in Figures 6.6 and 6.7.

In Figures 6.6 and 6.7, the slopes increase as the level of the reference noise increase, consistent with subjects giving either: (i) reduced discomfort ratings for the lower magnitudes of vibration relative to the higher levels of the reference noise (lower left of Figures 6.6 and 6.7), or (ii) increased discomfort ratings for the higher magnitudes of vibration relative to the higher levels of the reference noise (lower right of Figures 6.6 and 6.7), or (iii) increased discomfort ratings for the lower magnitudes of vibration relative to the lower levels of the reference noise (upper left of Figures 6.6 and 6.7), or (iv) lower discomfort ratings for the higher magnitudes of vibration relative to the lower levels of the reference noise (upper right of Figures 6.6 and 6.7).

It would appear that a masking effect could fully explain the findings: when subjects focused on the vibration, their perceptions of the lower magnitudes of vibration (lower left of Figures 6.6 and 6.7) may be masked by the higher levels of noise. The masking effect reduced as the magnitude of vibration increased (moving to the right in Figures 6.6 and 6.7) and as the level of the noise reduced (moving up in Figures 6.6 and 6.7). Similar to the situation when subjects focused on the noise, a range effect does not fully explain the findings. Although there may have been both a range effect and a masking effect, the masking effect was greater than any range effect, and the findings could be fully explained by some form of masking of vibration by the noise.

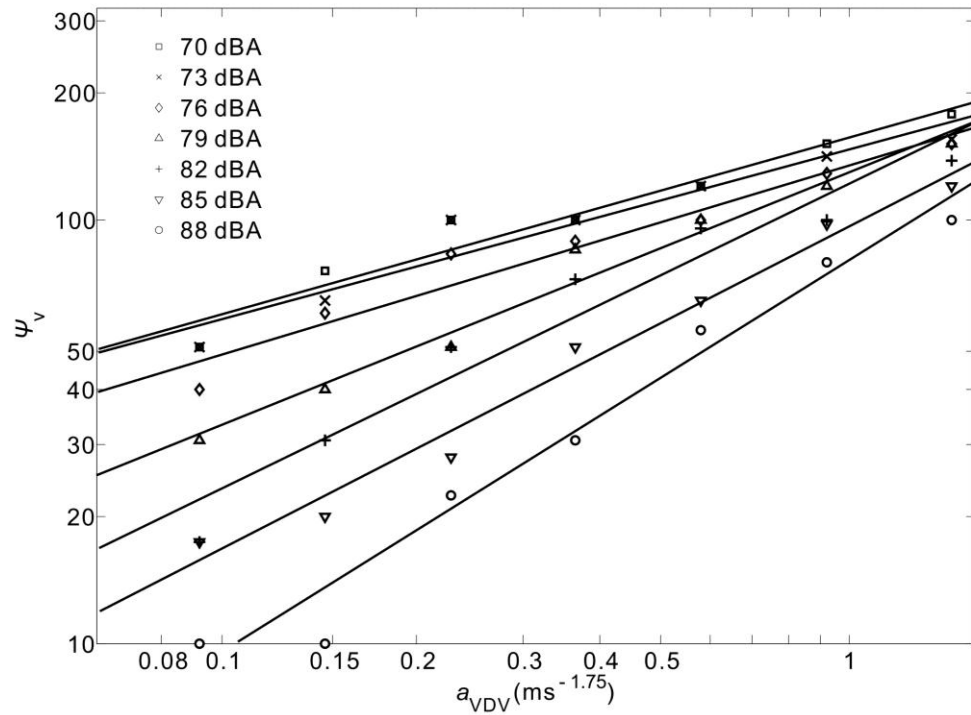


Figure 6.6 Linear regressions between the logarithm of the subjective magnitudes of vibration discomfort and a_{VDV1} when judged relative to 7 different levels of simultaneous noise. Medians from 20 subjects.

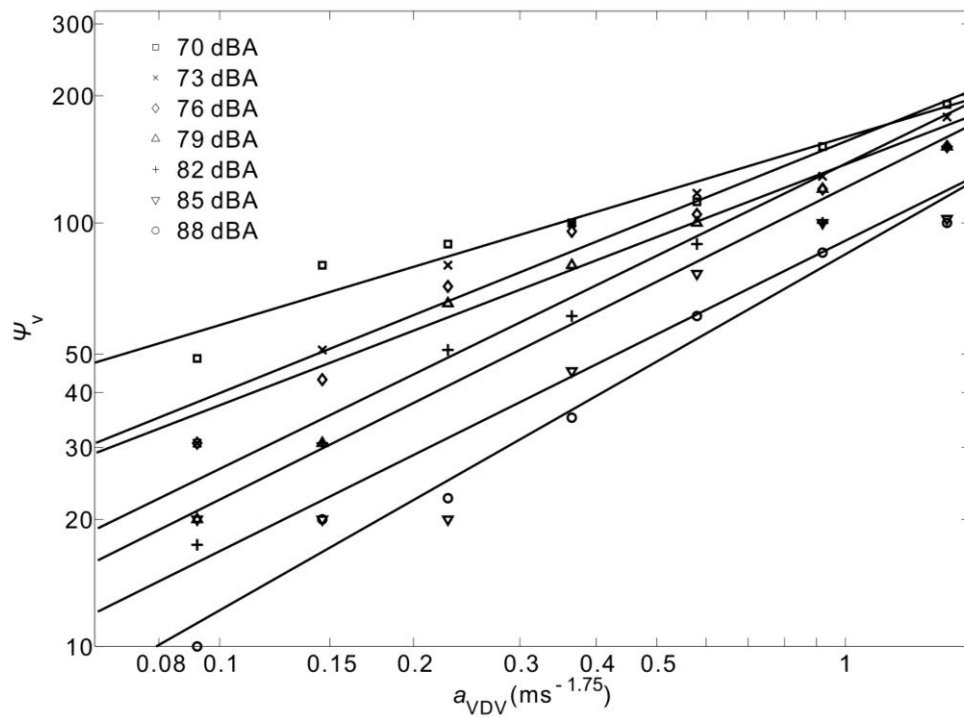


Figure 6.7 Linear regressions between the logarithm of the subjective magnitudes of vibration discomfort and a_{VDV2} when judged relative to 7 different levels of sequential noise. Medians from 20 subjects.

It is possible that the higher magnitudes of the vibration test stimuli masked the lower levels of the noise reference stimuli (upper right of Figures 6.6 and 6.7). If this occurred, subjects will have increased their subjective magnitudes for the higher magnitudes of the vibration test stimuli because the subjective magnitude of the noise reference was reduced as a result of masking by the vibration. Any overestimate of the subjective ratings may have been reduced to some extent by the range effect.

It seems that noise may have masked the subjective magnitude of vibration no matter whether the noise and vibration were presented simultaneously or sequentially: in both Figures 6.6 and 6.7 the slopes of the regressions between the individual judgements of the subjective magnitude of vibration and the physical magnitude of vibration reduced as the level of the noise reduced (Friedman, $p < 0.05$). The apparent influence of the noise on judgements of vibration was less when the stimuli were presented sequentially than when they were presented simultaneously: the differences in subjective magnitudes for the same physical magnitude of vibration between Figures 6.6 and 6.7 reduced as the level of the noise reduced, although none of the differences were statistically significant. The same tendency is apparent in Figure 6.2: the equivalent comfort contours obtained in session B (simultaneous noise and vibration) and session D (sequential noise and vibration) differ with low magnitude vibration (although not significantly) but become more similar as the vibration magnitude increases. This may be consistent with Kirby *et al.* (1977) who studied the ride quality of sinusoidal vertical vibration and broad-band noise presented simultaneously and concluded that the response was caused by both vibration and noise when there were relatively low levels of the stimuli but that the effect of the noise diminished as the level of the vibration increased.

The findings indicate it may be necessary to include a masking effect of noise on judgements of the discomfort caused by low magnitude vibration within any prediction of the relative (and combined) importance of noise and vibration, irrespective of whether the vibration and noise are simultaneous or sequential. Comparing Figures 6.4 and 6.5 with Figures 6.6 and 6.7, the judgement of vibration seems more likely to be influenced by the noise when vibration is the principal dependent variable than the judgment of noise is influenced by vibration when noise is the principal dependent variable. This is consistent with the findings of Paulsen and Kastka (1995) and might be influenced by the subjects being less familiar with judging vibration.

6.4.4 Application of results

To determine which of the two stimuli, noise or vibration, causes greater discomfort when they occur together, the summary information in Figure 6.2 may be useful. If a combination of noise and vibration falls to the left of (or above) an appropriate equivalence curve, a reduction of noise will be more beneficial. If a combination of noise and vibration falls to the right of (or below) the equivalence curve, a reduction of vibration will be more beneficial.

For sound levels greater than 60 dBA, if noise is the principal dependent variable, the equivalence found in sessions A and C may be appropriate, where the average value of the two intercepts, 81.0 dB, and the average slope, 12.7, can be used to approximate Equations (6.1)

and (6.2) to within 1.5 dB. If vibration is the principal dependent variable, the equivalence found in sessions B and D may be appropriate, where the average intercept, 84.6 dB, and the average slope, 31.5, approximate equations (6.3) and (6.4) to within 1 dB.

6.5 Conclusion

The subjective equivalence between noise and vibration depends on whether the discomfort caused by noise is judged relative to the discomfort caused by vibration (i.e., noise is the principal dependent variable), or the discomfort caused by vibration is judged relative to the discomfort caused by noise (i.e., vibration is the principal dependent variable). The subjective equivalence of noise and vibration is not greatly affected by whether the noise and vibration are presented simultaneously or sequentially.

When judging the discomfort caused by noise, higher magnitude vibrations tend to mask the discomfort caused by low levels of noise, and the equivalence between noise and vibration may be described by $L_{AE} = 81.0 + 12.7 \log_{10}(a_{VDV})$. When judging the discomfort caused by vibration, higher level noises tend to mask the discomfort caused by low magnitudes of vibration, and the equivalence between noise and vibration may be described by $L_{AE} = 84.6 + 31.5 \log_{10}(a_{VDV})$. With the levels of noise and the magnitudes of vibration used (i.e., SELs from 70 to 88 dBA and VDV_s from 0.092 to 1.458 ms^{-1.75}), the judgement of vibration is more influenced by noise than the judgment of noise is influenced by vibration.

It may be necessary to incorporate masking effects in any method of predicting the relative or combined importance of noise and vibration. A range effect may cause underestimation of the subjective magnitudes of high physical magnitudes of stimuli, and overestimation of the subjective magnitudes of low physical magnitudes of stimuli, but the range effect may be less important than the masking effect.

Chapter 7: Effect of durations on the relative discomfort of noise and vibration

7.1 Introduction

Noise and vibration influence the comfort experienced in land vehicles, aircraft, ships, and buildings. Studies of the relative importance of noise and vibration in causing discomfort have investigated the subjective equivalence of the SPL of noise and the r.m.s. acceleration of vibration (e.g., Hempstock and Saunders, 1973, 1976; Fleming and Griffin, 1975; Kjellberg *et al.*, 1985). The subjective equivalence of noise and vibration in buildings has been investigated using the sound exposure level, SEL, and the vibration dose value, VDV, so as to account for the influence of the intensity, the duration, and the frequency of the noise and vibration on human sensations (Howarth and Griffin, 1990a, 1990b, and 1991). The subjective equivalence of the SEL and the VDV associated with the noise and vibration in cars has also been investigated and compared with previous studies of the equivalence between the SPL and the r.m.s. acceleration (Huang and Griffin, 2012).

From Section 2.3.4, if the noise and vibration have fixed duration, the subjective equivalence of the stimuli may be adequately described by their r.m.s. levels, L_{Aeq} and a_{rms} , by:

$$L_{Aeq} = k' + 20 \frac{n'_v}{n'_s} \log_{10}(a_{rms}), \quad (7.1)$$

where k' is a constant (dB).

With noises and vibrations of variable duration, it seems more appropriate to express the equivalence between noise and vibration in terms of the SEL, L_{AE} , and the VDV, a_{VDV} , that reflect the expected increases in noise loudness and vibration discomfort associated with increases in the durations of noise and vibration. From Section 2.3.4, with noise and vibration of variable duration the subjective equivalence between the stimuli may be adequately described by their 'dose' values, L_{AE} and a_{VDV} , by:

$$L_{AE} = k + 20 \frac{n_v}{n_s} \log_{10}(a_{VDV}), \quad (7.2)$$

where k is a constant (dB).

These relationships imply that when presented on a graph of $\log_{10}(a_{rms})$ versus L_{Aeq} , or presented on a graph of $\log_{10}(a_{VDV})$ versus L_{AE} , the subjective equivalence between noise and vibration should have a slope of s' (i.e., $20(n'_v/n'_s)$) or s (i.e., $20(n_v/n_s)$). However, one or both of the slopes will depend on the duration of the stimuli because the time-dependency used to express exposure to noise (in the SEL) differs from the time-dependency used to express exposure to vibration (in the VDV). With stimuli of constant magnitude, the L_{AE} increases by 3 dB (i.e., $\sqrt{2} \approx 41\%$) when the duration of noise doubles, whereas a_{VDV} increases by only 1.5 dB

(i.e. $\sqrt[3]{2} \approx 19\%$) when the duration of vibration doubles. If both the SEL and the VDV have “correct” time-dependencies (or the correct ratio of time-dependencies), the slope, s , (i.e., $20(n_v/n_s)$ in Equation (7.2)) will not change with changes in the durations of the stimuli, but the slope, s' , in Equation (7.1) will increase with increasing duration of noise and vibration, because with increasing duration, L_{AE} increases more rapidly than a_{VDV} . If the equivalence between noise and vibration is determined solely by average measures of the two stimuli (i.e., L_{Aeq} and a_{rms}), and is therefore independent of the durations of the stimuli, the slope, s' , (i.e., $20(n'_v/n'_s)$ in Equation (7.1)) will not change, and the slope, s , in Equation (7.2) will increase with increasing duration of noise and vibration, because with increasing duration, L_{AE} increases more rapidly than a_{VDV} .

The subjective equivalence between noise and vibration obtained by Howarth and Griffin (1990b) with 24-s stimuli is given by either $L_{Aeq} = 88.2 + 25.1 \log_{10}(a_{rms})$ or $L_{AE} = 89.2 + 29.3 \log_{10}(a_{VDV})$ (i.e., a slope of 25.1 when using average measures and a slope of 29.3 when using dose measures). With shorter duration stimuli, such as 10-s stimuli used by Fleming and Griffin (1975) and 4-s stimuli used by Huang and Griffin (2010), similar slopes are obtained when using average measures (i.e., SPL and r.m.s. acceleration) or dose measures (i.e., SEL and VDV). With 1-s stimuli, the same slope is obtained irrespective of whether the average measures or the dose measures are used. The slopes obtained in different studies cannot be used to determine whether the slope s' or the slope s increases with the increasing duration because they have been obtained with different experimental conditions (different stimuli with differing physical magnitudes and frequencies, and different psychophysical methods, subjects, etc.).

A previous study in Chapter 6 has found that the subjective equivalence between noise and vibration appears to depend on whether noise is judged relative to vibration or vibration is judged relative to noise. When judging noise, higher magnitude vibrations appeared to mask the discomfort caused by low levels of noise, and when judging vibration, higher levels of noise appeared to mask the discomfort caused by low magnitudes of vibration. The judgement of vibration discomfort was more influenced by noise than the judgment of noise discomfort was influenced by vibration. The dependence of the subjective equivalence of noise and vibration on the durations of the stimuli, as reflected in the slopes s' and s , may therefore also depend on whether the discomfort produced by noise is judged relative to the discomfort produced by vibration or the discomfort produced by vibration is judged relative to the discomfort produced by noise.

This study was designed to investigate how the subjective equivalence of noise and vibration depends on the durations of the stimuli. Assuming r.m.s. measures of noise and vibration indicate the subjective equivalence between noise and vibration over a range of durations, it was hypothesised that if the subjective equivalence between noise and vibration is expressed in terms of the ‘dose’ of noise and the ‘dose’ of vibration (i.e., Equation (7.2)), the slope, s (i.e., $20(n_v/n_s)$), will increase as the durations of the stimuli increases. With all durations of the stimuli,

it was hypothesised that the slope obtained when judging noise relative to vibration would be less than the slope obtained when judging vibration relative to noise.

7.2 Method

7.2.1 Subjects

Fifteen male subjects, with median age 24 years (range 20 to 29 years), stature 174 cm (range 165 to 196 cm), and weight 72 kg (range 52 to 115 kg) volunteered to take part in the experiment. The subjects were all students at the University of Southampton.

7.2.2 Stimuli

Seven levels of random sound band-pass filtered between 50 and 500 Hz were generated with SPLs ranging from 64 to 82 dBA in 3-dB steps (International Organization for Standardization, 2003a). Seven magnitudes of random vibration band-pass filtered between 5 and 10 Hz were generated from 0.05 to 0.792 r.m.s. acceleration in 2 dB steps, using frequency weighting W_b (British Standards Institution, 1987). The exposure durations of the vibration and the sound stimuli used in the experiment were 2, 4, 8, 16, and 32 s, with a 0.2-s cosine taper at the start and end. The SEL for the five durations of the sound stimulus and the VDV for the five durations of vertical vibration are listed in Tables 7.1 and 7.2.

7.2.3 Procedure

Table 7.1 The SELs (dBA) of the sound stimuli of different levels and durations.

Duration (s)	L_{Aeq} (dBA)						
	64	67	70	73	76	79	82
2	67	70	73	76	79	82	85
4	70	73	76	79	82	85	88
8	73	76	79	82	85	88	91
16	76	79	82	85	88	91	94
32	79	82	85	88	91	94	97

Table 7.2 The VDV ($\text{ms}^{-1.75}$) of the vibration stimuli of different magnitudes and durations.

Duration (s)	a_{rms} (ms^{-2})						
	0.050	0.079	0.126	0.199	0.315	0.500	0.792
2	0.073	0.122	0.193	0.305	0.482	0.762	1.203
4	0.092	0.145	0.230	0.363	0.573	0.906	1.431
8	0.109	0.172	0.271	0.429	0.677	1.070	1.691
16	0.129	0.204	0.322	0.509	0.805	1.271	2.009
32	0.154	0.243	0.384	0.607	0.960	1.516	2.396

Judgments of 'discomfort' were obtained using the method of RME. The sound and vibration stimuli of the same durations were presented simultaneously in pairs with one of the two stimuli identified as the reference stimulus.

The experiment was undertaken in two sessions on separate days. On each day there were five parts to the study, corresponding to the five stimulus durations: 2, 4, 8, 16, or 32 s. In each part, subjects provided magnitude estimates of the discomfort caused by each of the seven levels of one of the stimuli (noise or vibration) relative to the discomfort caused by each of the seven levels of the other stimulus (vibration or noise). On one day, subjects rated the discomfort of noise, assuming the discomfort caused by the vibration was 100. On the other day, subjects rated the discomfort of vibration, assuming the discomfort caused by the noise was 100. Subjects experienced the two sessions in a balanced order.

Subjects were provided with written instructions (Appendix A4) and then practiced magnitude estimation by judging some combined noise and vibration stimuli until they felt confident with magnitude estimation.

7.3 Results

7.3.1 Discomfort of test noises judged relative to reference vibrations

For each of the five stimulus durations, and each magnitude of the reference vibration, linear regression was performed between the median values of the dependent variable, $\log_{10}(\psi_s)$, and the independent variable, L_{AE} . The slopes, $n_s/20$, the intercepts, $\log_{10}(k_s)$, and the correlation coefficients are shown in Table 7.3. From these linear relationships, the SELs that produced discomfort equivalent to the reference vibration (i.e., a subjective magnitude of 100) were obtained and are shown in the L_{AE} column of Table 7.3. Similarly, the SPLs that produced discomfort equivalent to the reference vibration are shown in the L_{Aeq} column of Table 7.3.

Linear regression between the values of L_{AE} and $\log_{10}(a_{VDV})$ in Table 7.3 (in accord with Equation (7.2)) provides the subjective equivalence of simultaneous noise and vibration for each duration as given in Table 7.4. The results of linear regression between the L_{Aeq} and $\log_{10}(a_{rms})$ are also given in Table 7.4 (in accord with Equation (7.1)).

The same procedures were applied to the magnitude estimates provided by each subject. These showed significant increases in the slopes, s (i.e., $20(n_v/n_s)$), and the intercepts, k , in the linear regression between L_{AE} and $\log_{10}(a_{VDV})$ ($p < 0.01$, Friedman), and showed significant increases in the slopes, s' (i.e., $20(n'_v/n'_s)$), and the intercepts, k' , in the linear regression between L_{Aeq} and $\log_{10}(a_{rms})$ ($p < 0.01$, Friedman) as the durations of the stimuli increased from 2 to 32 s.

With stimuli having durations of 2 and 4 s, the slopes, $n_s/20$, in the linear relation between $\log_{10}(\psi_s)$ and L_{AE} increased when the magnitude of reference vibration increased ($p = 0.02$ for 2 s, and $p = 0.07$ for 4 s; Friedman). For the longer duration stimuli (i.e., 8, 16 and 32 s), the

slopes did not change when the magnitude of the reference vibration increased ($p > 0.25$; Friedman).

7.3.2 Discomfort of test vibrations judged relative to reference noises

For each of the five stimulus durations, and each level of the reference noise, linear regression was performed between all median values of the dependent variable, $\log_{10}(\psi_v)$, and the independent variable, $\log_{10}(a_{VDV})$. The slopes, the intercepts, and the correlation coefficients are shown in Table 7.5. From these linear relationships, the VDV_s that produced discomfort equivalent to the reference noise (i.e., a subjective magnitude of 100) were obtained and are shown in the a_{VDV} column of Table 7.5. Similarly, the vibration r.m.s. acceleration that produced discomfort equivalent to the reference sound are shown in the a_{rms} column of Table 7.5.

Table 7.3 Discomfort of noise judged relative to the discomfort of simultaneous vibration. Linear regression analysis showing the SEL, L_{AE} , equivalent to each reference VDV, a_{VDV} , for each stimulus duration.

Duration (s)	Slope ($n_s/20$)	Intercept ($\log_{10}(k_s)$) (dB)	Correlation (r_s^2)	a_{VDV} ($ms^{-1.75}$)	L_{AE} (dBA)	L_{Aeq} (dBA)
2	0.019	0.735	0.940	0.073	66.58	63.63
	0.020	0.650	0.937	0.122	67.50	64.60
	0.016	0.838	0.941	0.193	72.63	69.56
	0.018	0.691	0.877	0.305	72.72	69.67
	0.017	0.711	0.795	0.482	75.82	72.76
	0.014	0.913	0.834	0.762	77.64	74.64
	0.031	-0.551	0.952	1.203	82.29	79.26
4	0.020	0.572	0.949	0.092	71.40	65.40
	0.017	0.776	0.945	0.145	72.00	66.06
	0.016	0.809	0.956	0.230	74.44	68.38
	0.017	0.752	0.876	0.363	73.41	67.53
	0.017	0.663	0.943	0.573	78.65	72.65
	0.019	0.443	0.864	0.906	81.95	75.95
	0.021	0.138	0.951	1.431	88.67	82.57
8	0.019	0.600	0.961	0.109	73.68	64.68
	0.018	0.680	0.905	0.172	73.33	64.56
	0.016	0.821	0.891	0.271	73.69	64.94
	0.016	0.714	0.971	0.429	80.38	71.19
	0.014	0.811	0.902	0.677	84.93	75.64
	0.017	0.513	0.893	1.070	87.47	78.41
	0.024	-0.138	0.872	1.691	89.08	80.04
16	0.015	0.878	0.983	0.129	74.80	62.67
	0.018	0.637	0.932	0.204	75.72	63.94
	0.019	0.438	0.956	0.322	82.21	70.00
	0.017	0.621	0.920	0.509	81.12	69.06
	0.021	0.225	0.847	0.805	84.52	72.52
	0.020	0.292	0.951	1.271	85.40	73.70
	0.026	-0.399	0.972	2.009	92.27	80.12
32	0.014	0.954	0.941	0.154	74.71	59.64
	0.014	0.887	0.896	0.243	79.50	64.07
	0.016	0.699	0.906	0.384	81.31	66.44
	0.017	0.519	0.916	0.607	87.12	71.82
	0.017	0.489	0.915	0.960	88.88	73.76
	0.019	0.233	0.969	1.516	93.00	78.00
	0.029	-0.769	0.989	2.396	95.48	80.59

From Equations (7.1) and (7.2), the equivalence between the discomfort caused by simultaneous noise and vibration for each duration is given in Table 7.6 from the linear regressions between L_{AE} and $\log_{10}(a_{VDV})$, and between L_{Aeq} and $\log_{10}(a_{rms})$.

The same procedures were applied to the magnitude estimates provided by each subject. As the durations of the stimuli increased from 2 to 32 s, there were no significant differences in the slopes, s ($p = 0.33$, Friedman), but significant increases in the intercepts, k ($p < 0.01$, Friedman) in the regressions between L_{AE} and $\log_{10}(a_{VDV})$. Similarly, as the durations of the stimuli increased there were no significant differences in the slopes, s' ($p = 0.45$, Friedman), but significant increases in the intercepts, k' ($p = 0.03$, Friedman) in the regressions between L_{Aeq} and $\log_{10}(a_{rms})$, as the durations of the stimuli increased from 2 to 32 s.

With stimuli of all durations from 2 to 32 s, the slopes, n_v , in the linear relation between $\log_{10}(\psi_v)$ and $\log_{10}(a_{VDV})$ increased when the level of reference noise increased ($p < 0.01$, Friedman).

7.3.3 Contours of equivalence between sound and vibration

From Tables 7.4 and 7.6, contours showing the noise and vibration that produced equivalent discomfort at different durations were obtained when judging noise relative to vibration and when judging vibration relative to noise. These are shown in Figures 7.1 and 7.2 with coordinate axes of $\log_{10}(a_{VDV})$ versus L_{AE} , and in Figures 7.3 and 7.4 with coordinate axes of $\log_{10}(a_{rms})$ versus L_{Aeq} .

At each duration, the slopes, s and s' , were greater when judging vibration relative to noise than when judging noise relative to vibration ($p < 0.01$ for 2, 4, 8, 16 s, and $p = 0.012$ for 32 s; Wilcoxon). The intercepts, k , in the regressions between L_{AE} and $\log_{10}(a_{VDV})$ were greater when

Table 7.4 Subjective equality of discomfort between simultaneous noise and vibration of different durations, from judging discomfort of test noise relative to discomfort of reference vibration.

Duration (s)	Equivalent comfort contour	Correlation
2	$L_{AE} = 80.09 + 12.50 \log_{10}(a_{VDV})$	0.96
	$L_{Aeq} = 79.38 + 12.53 \log_{10}(a_{rms})$	0.96
4	$L_{AE} = 83.22 + 13.64 \log_{10}(a_{VDV})$	0.86
	$L_{Aeq} = 80.68 + 13.49 \log_{10}(a_{rms})$	0.86
8	$L_{AE} = 86.04 + 15.43 \log_{10}(a_{VDV})$	0.92
	$L_{Aeq} = 81.93 + 15.08 \log_{10}(a_{rms})$	0.92
16	$L_{AE} = 86.20 + 13.31 \log_{10}(a_{VDV})$	0.91
	$L_{Aeq} = 79.60 + 13.30 \log_{10}(a_{rms})$	0.91
32	$L_{AE} = 89.49 + 17.41 \log_{10}(a_{VDV})$	0.99
	$L_{Aeq} = 82.89 + 17.50 \log_{10}(a_{rms})$	0.99

judging vibration relative to noise than when judging noise relative to vibration at the durations of 2 and 8 s ($p < 0.01$, Wilcoxon) but did not differ at the other durations ($p = 0.08$ for 4 s, $p = 0.28$ for 16 s, and $p = 0.43$ for 32 s). The intercepts, k' , in the regressions between L_{Aeq} and $\log_{10}(a_{rms})$ were greater when judging vibration relative to noise than when judging noise relative to vibration at the durations of 2, 4, 8 and 16 s ($p < 0.01$, Wilcoxon) but were less at the duration of 32 s ($p < 0.01$, Wilcoxon).

Table 7.5 Discomfort of vibration judged relative to the discomfort of simultaneous noise. Linear regression analysis showing the VDV, a_{VDV} , equivalent to each reference SEL, L_{AE} , for each stimulus duration.

Duration (s)	Slope (n_v)	Intercept ($\log_{10}(k_v)$)	Correlation (r_v^2)	L_{AE} (dBA)	a_{VDV} (ms^{-2})	a_{rms} (ms^{-2})
2	0.187	2.153	0.932	67.0	0.152	0.101
	0.265	2.142	0.883	70.0	0.291	0.192
	0.282	2.139	0.902	73.0	0.321	0.211
	0.378	2.138	0.986	76.0	0.432	0.284
	0.516	2.096	0.974	79.0	0.652	0.427
	0.505	2.063	0.908	82.0	0.750	0.490
	0.613	1.973	0.983	85.0	1.107	0.721
4	0.190	2.145	0.932	70.0	0.173	0.094
	0.236	2.131	0.941	73.0	0.279	0.152
	0.306	2.130	0.974	76.0	0.376	0.207
	0.381	2.106	0.872	79.0	0.527	0.291
	0.477	2.084	0.882	82.0	0.667	0.367
	0.554	2.031	0.958	85.0	0.879	0.485
	0.550	1.926	0.958	88.0	1.365	0.755
8	0.268	2.169	0.948	73.0	0.234	0.108
	0.302	2.152	0.960	76.0	0.314	0.146
	0.345	2.114	0.904	79.0	0.468	0.217
	0.393	2.103	0.853	82.0	0.547	0.254
	0.382	2.054	0.946	85.0	0.723	0.337
	0.514	2.001	0.972	88.0	0.995	0.465
	0.643	1.937	0.957	91.0	1.253	0.586
16	0.225	2.109	0.981	76.0	0.328	0.128
	0.291	2.122	0.960	79.0	0.381	0.149
	0.364	2.095	0.930	82.0	0.548	0.215
	0.381	2.073	0.943	85.0	0.643	0.252
	0.408	2.036	0.924	88.0	0.817	0.321
	0.514	1.959	0.982	91.0	1.202	0.473
	0.603	1.888	0.976	94.0	1.535	0.603
32	0.252	2.134	0.960	79.0	0.294	0.095
	0.304	2.112	0.968	82.0	0.429	0.140
	0.385	2.063	0.961	85.0	0.685	0.224
	0.505	2.035	0.860	88.0	0.853	0.279
	0.528	1.999	0.934	91.0	1.005	0.330
	0.609	1.938	0.972	94.0	1.265	0.417
	0.649	1.829	0.921	97.0	1.832	0.605

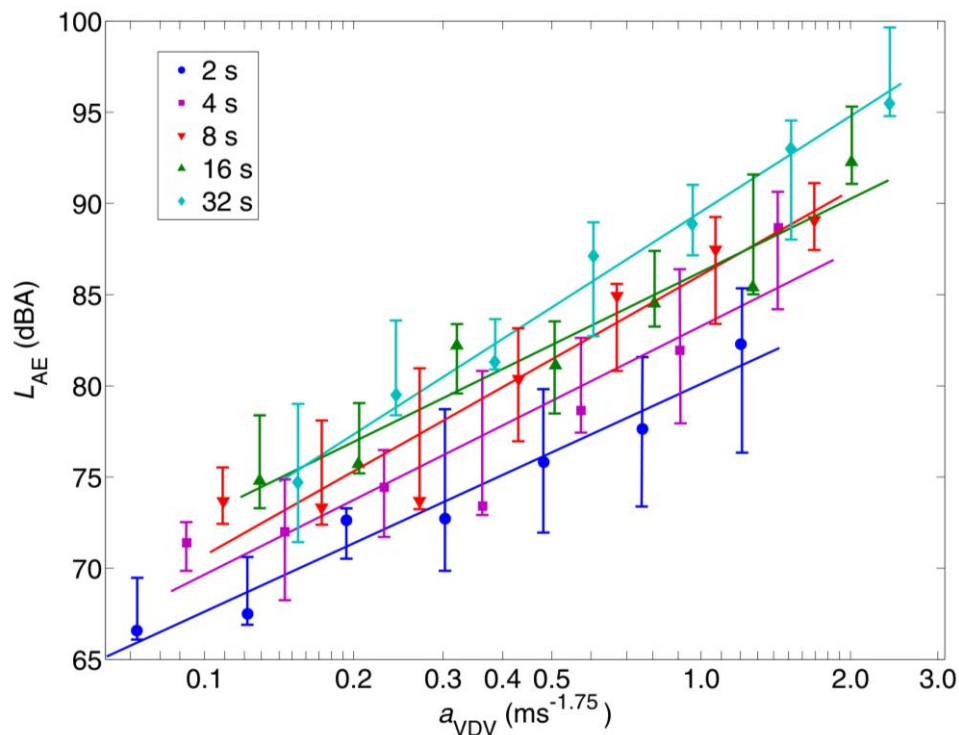


Figure 7.1 The subjective equivalence between noise (SEL) and vibration (VDV) with stimuli durations from 2 to 32 s when judging noise relative to vibration. Medians and inter-quartile ranges of 15 subjects.

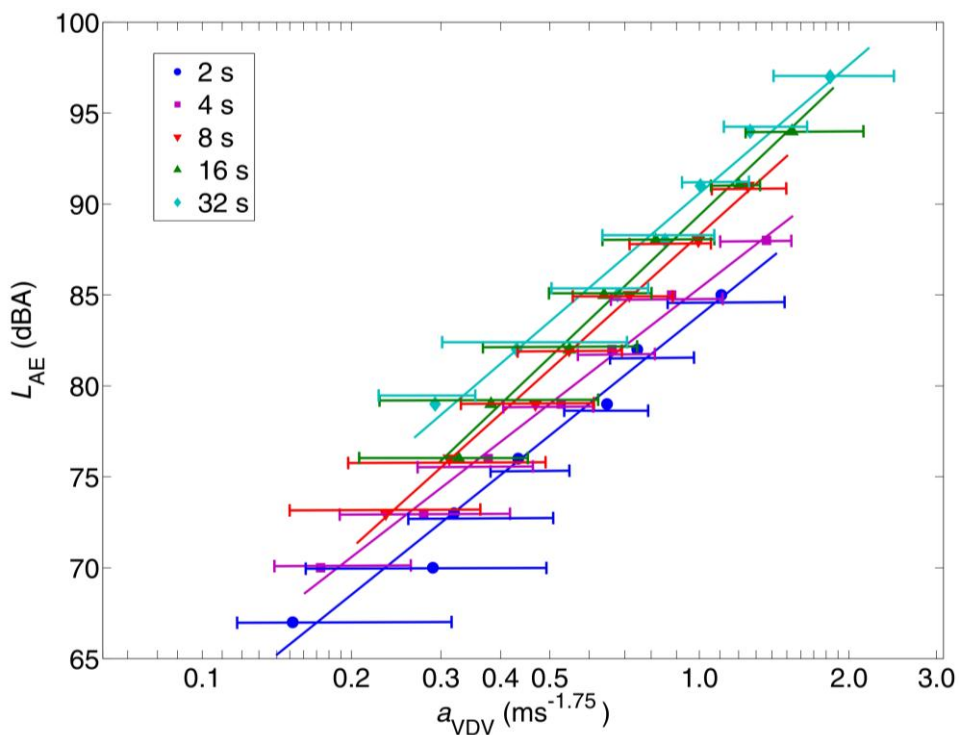


Figure 7.2 The subjective equivalence between noise (SEL) and vibration (VDV) with stimuli durations from 2 to 32 s when judging vibration relative to noise. Medians and inter-quartile ranges of 15 subjects.

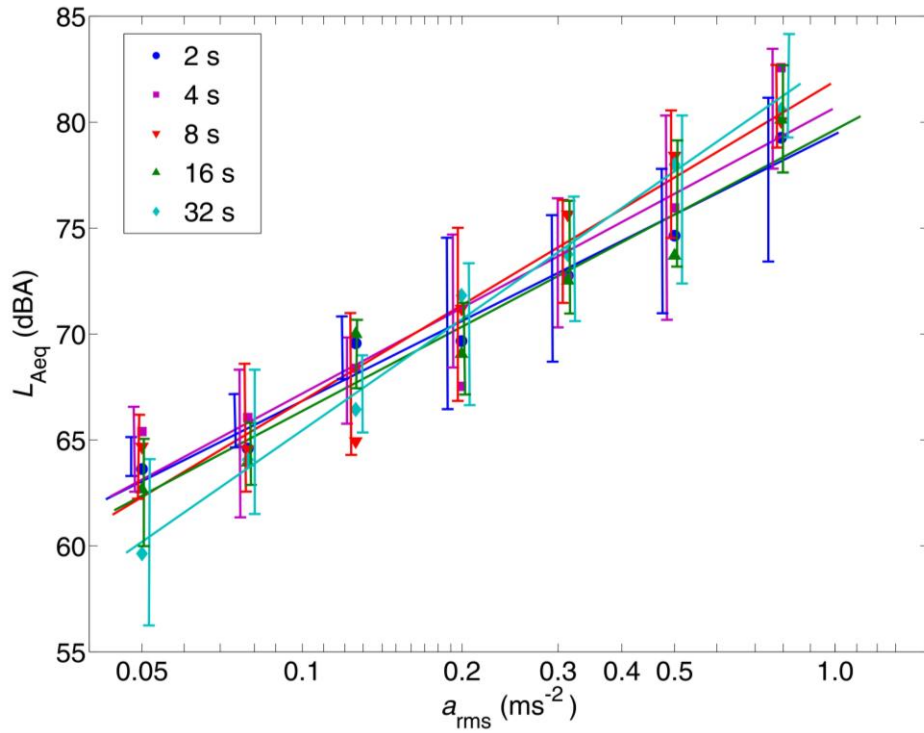


Figure 7.3 The subjective equivalence between noise (SPL) and vibration (r.m.s.) with stimuli durations from 2 to 32 s when judging noise relative to vibration. Medians and inter-quartile ranges of 15 subjects.

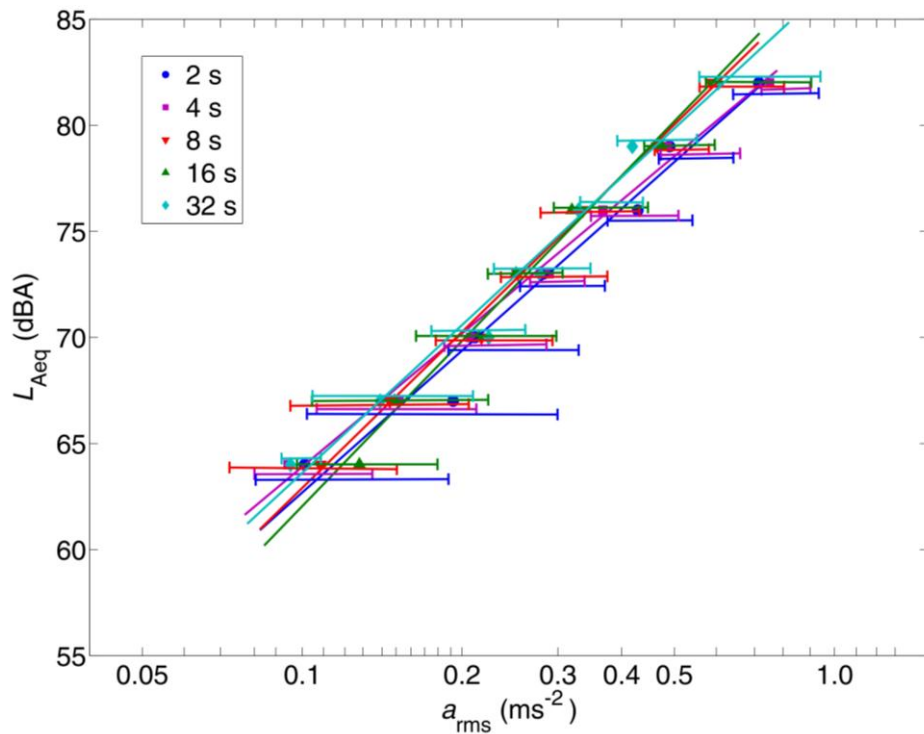


Figure 7.4 The subjective equivalence between noise (SPL) and vibration (r.m.s.) with stimuli durations from 2 to 32 s when judging vibration relative to noise. Medians and inter-quartile ranges of 15 subjects.

Table 7.6 Subjective equality of discomfort between simultaneous noise and vibration of different durations, from judging discomfort of test vibration relative to discomfort of reference noise.

Duration (s)	Equivalent comfort contour	Correlation
2	$L_{AE} = 83.78 + 21.98 \log_{10}(a_{VDV})$	0.97
	$L_{Aeq} = 84.93 + 22.22 \log_{10}(a_{rms})$	0.97
4	$L_{AE} = 85.40 + 21.13 \log_{10}(a_{VDV})$	0.99
	$L_{Aeq} = 84.79 + 20.98 \log_{10}(a_{rms})$	0.99
8	$L_{AE} = 88.26 + 24.71 \log_{10}(a_{VDV})$	0.99
	$L_{Aeq} = 87.38 + 24.55 \log_{10}(a_{rms})$	0.99
16	$L_{AE} = 89.40 + 26.12 \log_{10}(a_{VDV})$	0.99
	$L_{Aeq} = 87.96 + 26.01 \log_{10}(a_{rms})$	0.99
32	$L_{AE} = 90.57 + 23.48 \log_{10}(a_{VDV})$	0.99
	$L_{Aeq} = 86.83 + 23.29 \log_{10}(a_{rms})$	0.99

7.4 Discussion

7.4.1 Equivalence when judging noise relative to vibration or vibration relative to noise

With all five durations (i.e., 2, 4, 8, 16, and 32 s), when judging noise relative to vibration the five slopes of the equivalent comfort contours (12.5, 13.6, 15.4, 13.3, and 17.4) were significantly less than when judging vibration relative to noise (22.0, 21.1, 24.7, 26.1, and 23.5). However, both sets may be considered consistent with the findings of previous studies. When judging noise relative to vibration, the present study and previous studies in Chapters 5 and 6 have found values in the range of 12.4 to 17.4, and when asking subjects to indicate the subjective intensity of noise on a 9-point-scale, Paulsen and Kastka (1995) found a value of 13.7 (with tram noise) and 14.4 (with hammermill noise). When adjusting the level of noise to match vibration, Hempstock and Saunders (1976) found slopes in the range 16.2 to 29.1. In these studies, the discomfort caused by noise was the principal dependent variable (i.e., noise was judged relative to a reference vibration).

When judging vibration relative to noise, previous study in Chapter 6 found slopes of 30.4 or 32.6 and when adjusting vibration to match noise Hempstock and Saunders (1976) found slopes from 37.0 to 47.6 with an average slope of 43.5, both broadly consistent with the present study. In these studies, the discomfort caused by the vibration was the principal dependent variable.

When asking subjects to state the noise or the vibration they would prefer to reduce, Fleming and Griffin (1975) and Howarth and Griffin (1990a) obtained similar slopes of 33 and 29.3, respectively. Their slopes are similar to those obtained when judging vibration relative to noise in previous study (see Chapter 6), implying their subjects may have focused more on the

vibration than on the noise, possibly because the vibration was less familiar to subjects and so demanded their attention.

As suggested in Chapter 6, if asked to evaluate noise, subjects may focus on the modality 'noise', whereas if asked to evaluate vibration, or not told which modality (i.e., noise or vibration) to evaluate, subjects may focus on the more unusual modality of 'vibration'. Paulsen and Kastka (1995) concluded when subjects focused on the modality noise, their judgement would be affected by simultaneous vibration, when subjects focused on the modality vibration, their judgement would be independent of the simultaneous noise. However, it was found in Chapter 6 the judgement of vibration was greatly affected by noise when subjects judged discomfort produced by vibration relative to the noise. The difference may be because although the studies used similar magnitudes of vibration, Paulsen and Kastka used much lower levels of noise.

7.4.2 Influence of duration on the exponents of noise and vibration

When judging noise relative to vibration, for short durations of 2 and 4 s, the exponent n_s (i.e., the slope $n_s/20$ in the relation between $\log_{10}(\psi_s)$ and L_{AE}) increased as the magnitude of the simultaneous reference vibration increased. This is consistent with a previous study in which the exponent n_s increased when judging the discomfort of noise relative to 4-s reference vibrations of increasing magnitude, where it was concluded that the discomfort produced by low levels of noise were underestimated due to 'masking' by high magnitudes of vibration (see Section 6.4.2). When the duration was increased to 8 s or longer in the present experiment, the exponent n_s did not vary with the magnitude of the simultaneous vibration, possibly because the influence of vibration decreased as the durations of both stimuli increased.

When judging vibration relative to noise, for all durations from 2 to 32 s, the exponent n_v (i.e., the slopes, n_v , in the linear relation between $\log_{10}(\psi_v)$ and $\log_{10}(a_{VDV})$) increased when the levels of the simultaneous reference noise increased. This is also consistent with a previous finding that the exponent n_v increased as the level of a reference noise increased when judging vibration discomfort relative to noise discomfort with 4-s stimuli, and it was concluded that the discomfort produced by low magnitudes of vibration were underestimated due to 'masking' by high levels of noise (see Section 6.4.3). It seems that this influence of noise on judgements of vibration discomfort is independent of stimulus duration (up to 32 s).

7.4.3 Influence of duration on the relative importance of noise and vibration

From Figures 7.1 and 7.2 it may be concluded that the combination of SEL and VDV does not provide a good basis for expressing the relative discomfort caused by noise and whole-body vibration over a range of durations. In contrast, Figures 7.3 and 7.4 suggest the SPL and the r.m.s. acceleration may provide a useful indication of the equivalence between the stimuli, at least over durations from 2 to 32 s. Over this range of durations, with VDV varying from 0.073 to $2.396 \text{ ms}^{-1.75}$ (Table 7.2), using SEL and VDV the range of median SEL varied from 4.2 to 11.3 dB when judging noise relative to vibration (Table 7.4) or, with SEL varying from 67 to 97 dBA (Table 7.2), using SEL and VDV the range of median VDV varied from 1.7:1 to 2.1:1 error in

VDV (Table 7.6). The ranges are far less when using the SPL and r.m.s. acceleration, with the range of median SPL from 3.0 to 3.0 dB when judging noise relative to vibration (over the range of 0.050 to 0.792 ms⁻² r.m.s.) and the range of median r.m.s. acceleration from 1.2:1 to 1.3:1 when judging vibration relative to noise (over the range of 64 to 82 dBA SPL).

This study does not indicate that both SEL and VDV have incorrect time-dependencies, but it does indicate that, at least, either SEL has an inappropriate time-dependency in respect of the discomfort caused by noise or VDV has an inappropriate time-dependency in respect of the discomfort caused by vibration. The similarity in the equivalence between SPL and r.m.s. acceleration over the range 2 to 32 s suggests the time-dependency for noise and vibration should be similar, yet SEL increases by 3 dB when the duration of noise doubles and VDV increases by only 1.5 dB when the duration of vibration doubles. Studies of the duration-dependence of vibration discomfort have found slopes around, or slightly greater than, 1.5 dB per doubling of vibration duration (Griffin, 1990). Studies with noise have used loudness or annoyance rather than 'discomfort' as the dependent variable. Loudness increases by about 10 phon (in loudness level) for each 10-fold increase in duration up to about 0.1 s, and is almost independent of duration in the range 0.1 to 1.0 s (e.g., Zwicker and Fastl, 1999). Studies have found wide ranges of the slope of the duration-dependence of noise annoyance. For example, slopes from 0.6 to 3.1 dB with a median slope of 2.0 dB per doubling of duration from 1 to 34 s (Little and Mabry, 1968), and 3.4 dB per doubling of duration from 0.03 to 90 s (Hiramatsu *et al.*, 1978). The convenient slope of 3 dB per doubling of duration, as embodied in the standardized measurement of SEL (e.g., International Organization for Standardization, 2003a) may overestimate the effect of duration on the discomfort caused by noise.

7.4.4 Time-dependence of the slope in the equivalent comfort contour between noise and vibration

The study does not reveal how the exponents (n_s and n_v) depend on the durations of the stimuli (noise and vibration) but it shows how their ratio (i.e., n_v/n_s) varies with stimulus duration. The slope, s' (i.e., $20(n'_v/n'_s)$ in Equation (7.1)), is similar to the slope, s (i.e., $20(n_v/n_s)$ in Equation (7.2)), over durations from 2 to 32 s. The slope, s (or s') in the regressions between L_{AE} and $\log_{10}(a_{vdv})$ (or between L_{Aeq} and $\log_{10}(a_{rms})$) depended on the stimulus duration when noise was judged relative to vibration but not when judging vibration relative to noise. The slope, s , is plotted as a function of duration in Figure 7.5.

When judging noise relative to vibration, an exponential relationship might be assumed between the slope, s (i.e., $20(n_v/n_s)$) and the duration, t :

$$s = s_0(t/t_0)^{n_t}, \quad (7.3)$$

where s_0 is a constant, $t_0 = 1$ s, and n_t is the exponent. From Table 7.4 and Figure 7.5, the dependence of s on the duration t is obtained by linear regression in the logarithmic form as:

$$\log_{10}(s) = 1.07 + 0.092 \log_{10}(t/t_0), \quad (7.4)$$

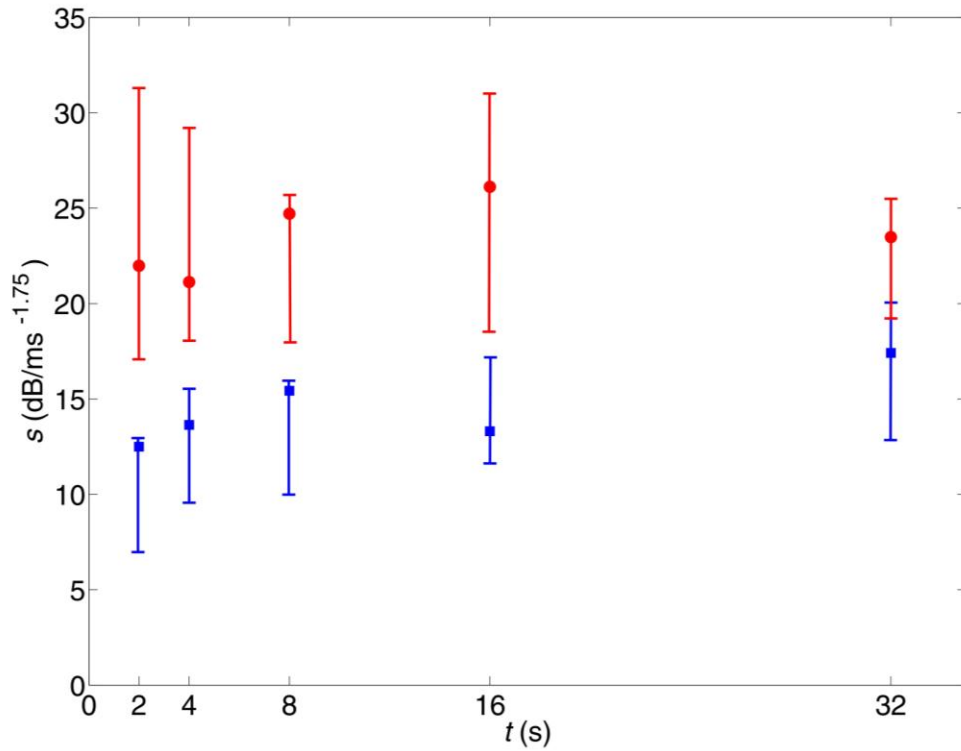


Figure 7.5 The slopes of subjective equivalence between noise and vibration for durations from 2 to 32 s. Medians of individual and inter-quartile ranges from 15 subjects. ■ judging noise relative to vibration, ● judging vibration relative to noise.

with a correlation coefficient of 0.70 ($p < 0.01$, Spearman). So

$$s = 11.75(t/t_0)^{0.092}. \quad (7.5)$$

When judging vibration relative to noise, the slope, s , did not change significantly with the durations of the stimuli when their magnitudes were expressed in terms of L_{AE} and a_{VDV} , and the median value of 23.5 for the slopes in Table 7.6 seems to be appropriate.

The increase in the slopes s (i.e., $20(n_v/n_s)$) and s' (i.e., $20(n'_v/n'_s)$) with increasing duration when noise was judged relative to vibration but not when vibration was judged relative to noise might be explained by judgements of noise relative to vibration being affected by the simultaneous vibration, with the influence of vibration decreasing as the duration increased. The judgement of vibration may have been affected by the simultaneous noise but with the influence of the noise independent of the duration, so the slope did not change.

It might be expected that with long duration stimuli the slope would be the same when judging noise relative to vibration and when judging vibration relative to noise. From Equation (7.4), when judging noise relative to vibration, the slope s will become 23.5, the median value when judging vibration relative to noise, at 33 minutes. Possibly, after long exposures to simultaneous noise and vibration, if a noise is considered to cause similar discomfort to a vibration, the vibration may be considered to cause similar discomfort to the noise.

7.5 Conclusion

The principal standardised 'dose' measures for human responses to sound and vibration (i.e., SEL and VDV) are not more effective than average measures (i.e., SPL and r.m.s. acceleration) for predicting the relative discomfort of noise and whole-body vibration over durations from 2 to 32 s. The findings suggest the rate of increase in discomfort with increasing duration should be similar for noise and vibration, whereas they are currently assumed to be 3 dB per doubling of noise duration and 1.5 dB per doubling of vibration duration.

The discomfort caused by low levels of noise may be masked by high magnitudes of vibration, and the discomfort caused by low magnitudes of vibration may be masked by high levels of noise. As the durations of the stimuli increase from 2 to 32 s, the influence of vibration on the judgement of noise discomfort decreases, whereas the influence of noise on the judgement of vibration discomfort does not change.

The slopes s (in terms of SEL and VDV) or s' (in terms of SPL and r.m.s. acceleration) expressing the levels of noise judged equivalent to various magnitudes of vibration are less when judging noise discomfort relative to vibration discomfort than when judging vibration discomfort relative to noise discomfort. Over durations from 2 to 32 s, the slopes increased with increasing duration when judging noise relative to vibration, and were independent of duration when judging vibration relative to noise.

Chapter 8 Comparison of absolute and relative magnitude estimation methods for judging the discomfort of noise and vibration

8.1 Introduction

The method of magnitude estimation was developed to obtain quantitative judgements of the perceived magnitude of stimuli (e.g., Stevens, 1955, 1956, 1986). A sensation produced by a stimulus is rated numerically by an observer using either any number (in the absolute method of magnitude estimation), or relative to a number associated with the sensation produced by a reference stimulus (in the relative method of magnitude estimation). Stevens' power law shows how the subjective magnitude, ψ , grows as a power of the stimulus magnitude, ϕ :

$$\psi = k\phi^n, \quad (8.1)$$

where k is a constant that depends on the units of measurement and the exponent, n , is the rate of growth of subjective sensations, which differs according to the sensation (Stevens, 1986).

The absolute method of magnitude estimation was based on evidence that subjects tend to use absolute scales rather than ratio scales for judging stimuli (e.g., Hellman and Zwislöcki, 1968). Zwislöcki and Goodman (1980) argued that the absolute method of magnitude estimation was relatively free of biases due to contextual effects (such as the order of the presented stimuli, the range of stimuli, the range of numbers, the level of stimuli relative to the reference), and that it could provide an 'absolute' scale of sensory magnitudes. Mellers (1983) argued that removing the constraints of a standard (the reference stimulus) and the modulus (the numerical value of the reference, for example '100') did not yield an 'absolute' scale of sensation, and that absolute scaling increased response variability and thereby lowered the statistical power of a subjective test.

Irrespective of whether the absolute method of magnitude estimation avoids contextual effects and yields an 'absolute' scale of sensory magnitude, the absolute method is popular and has yielded apparently useful results, especially in determining exponents for scaling the subjective magnitude of sound (e.g., Zwislöcki and Goodman, 1980; Hellman, 1976, 1983; Stevens, 1986; Ward *et al.*, 1996). The relative method of magnitude estimation is also widely used in determining exponents for the subjective magnitude of sound (e.g., Stevens, 1986; Ward *et al.*, 1996) and vibration (e.g. Shoenberger and Harris, 1971; Morioka and Griffin, 2006).

When comparing subjective magnitudes of the 'discomfort' produced by noise and whole-body vibration, the relative method of magnitude estimation has been used to judge noise relative to a vibration reference and to judge vibration relative to a noise reference (e.g., Jones and Saunders, 1974; Howarth and Griffin, 1988; Huang and Griffin, 2010). The absolute method of magnitude estimation has not been used to compare noise and vibration stimuli.

This study investigated the reliability of the two methods of magnitude estimation, 'relative magnitude estimation' (RME) and 'absolute magnitude estimation' (AME), in rating the discomfort associated with noise and whole-body vibration. An experiment was designed to investigate whether the RME and AME methods yield the same relationships between the physical magnitudes of the stimuli (i.e., noise and vibration) and their subjective magnitudes. The reliability of RME and AME methods (i.e., degree to which they produce similar values when applied repeatedly) were compared based on their consistency (i.e., correlations between magnitude estimates when applied repeatedly) and inter-subject variability.

8.2 Methods

8.2.1 Subjects

Twenty healthy subjects (10 male and 10 female), with median age 24 years (range 22 to 29 years), stature 166.5 cm (range 160 to 196 cm), and weight 57.5 kg (range 41 to 103 kg) volunteered to take part in the experiment. The subjects were students of the University of Southampton.

8.2.2 Stimuli

Thirteen levels of random noise, band-pass filtered between 50 and 500 Hz, were generated with SPLs (L_{Aeq}) ranging from 64 to 82 dBA in 1.5 dB steps (International Organization for Standardization, 2003a). Thirteen magnitudes of random vibration, band-pass filtered between 5 and 10 Hz, were generated from 0.05 to 0.792 ms^{-2} r.m.s. acceleration (a_{rms}) in 1 dB steps (using frequency weighting W_b ; British Standards Institution, 1987). The vibration and sound stimuli had durations of 4 s with a cosine taper applied to the first and last 0.2 s.

8.2.3 Procedure

Judgments of 'discomfort' were obtained using the two magnitude estimation methods: the AME method and the RME method. The experiment was implemented in two sessions. Each session was implemented in two parts. In session A, subjects first rated the thirteen magnitudes of vibration using the RME method, and then rated the thirteen levels of noise using the AME method. In session B, subjects first rated the thirteen levels of noise using the RME method, and then rated the thirteen magnitudes of vibration using the AME method. The subjects experienced the two sessions on separated days, with ten subjects commencing with session A (Group 1) and 10 subjects commencing with session B (Group 2).

When rating vibration using the RME method, subjects were presented with a 'reference vibration' at 0.199 ms^{-2} r.m.s. followed by a 'test vibration' and asked to state the discomfort caused by the test vibration, assuming the discomfort caused by the reference vibration was 100. When rating noise using the RME method, subjects were presented with a 'reference noise' at 73 dBA followed by a 'test noise' and asked to state the discomfort caused by the test noise, assuming the discomfort caused by the reference noise was 100. When rating vibration

or noise using the AME method, subjects were presented with the vibration or noise stimuli and asked to give any numerical values they wished to quantify their discomfort.

With both the RME method and the AME method the thirteen test stimuli were presented in independent random orders. In both sessions, all stimuli were judged using the RME method three times prior to starting with the AME method, which was also repeated three times. The duration of each session of the experiment was around fifteen minutes.

Before commencing each part of the experiment, subjects were provided with written instructions (Appendix A5) and practiced magnitude estimation with the appropriate method (RME or AME) and noise or vibration stimuli having, successively, median, high, and low magnitudes until they felt confident with magnitude estimation.

After finishing the experiment, subjects responded to three forced-choice questions: “1. Which method was easier for you to rate – with reference, or without reference?”, “2. Overall, which did you feel more uncomfortable – noise or vibration?” and “3. Which stimulus was easier for you to rate – noise or vibration?”

According to Stevens’ power law (Stevens, 1986), the subjective magnitude of noise, ψ_s , and the subjective magnitude of vibration, ψ_v , are related to the physical magnitude of sound, ϕ_s , and the physical magnitude of vibration, ϕ_v , by power functions:

$$\psi_s = k_s \phi_s^{n_s} \quad (8.2)$$

$$\psi_v = k_v \phi_v^{n_v} \quad (8.3)$$

where k_s and k_v are constants, and n_s and n_v are the rates of growth of subjective sensations produced by the sound and the vibration, respectively (see also Sections 2.3.2 and 2.3.3).

In terms of logarithms, the power law equations become:

$$\log_{10}(\psi_s) = \log_{10}(k_s) + (n_s/20) L_{Aeq} \quad (8.4)$$

where $L_{Aeq} \propto 20 \log(\phi_s)$ is the equivalent continuous A-weighted SPL (International Organization for Standardization, 2007), assuming ϕ_s represents the A-weighted sound pressure in Equation (8.2), and

$$\log_{10}(\psi_v) = \log_{10}(k_v) + n_v \log_{10}(a_{rms}) \quad (8.5)$$

where $a_{rms} \propto \phi_v$ is the W_b -weighted r.m.s. acceleration of the vibration stimulus (British Standards Institution, 1987).

Magnitude estimates obtained from each individual using the AME method were divided by the median of their magnitude estimates over all stimuli, and then multiplied by ‘100’ (Stevens, 1971). This ‘normalized’ the magnitude estimates so that the AME and RME data could be analysed using the same procedures and compared.

8.3 Results

8.3.1 General results

From the questionnaire, 85% of subjects thought RME was easier than AME. Overall, 75% of subjects felt that the noise was more uncomfortable, but 75% of subjects thought the vibration was easier to rate.

The magnitude estimates of discomfort associated with the thirteen levels of noise, and the magnitude estimates of discomfort associated with the thirteen magnitudes of vibration, are shown for both RME and AME in Figure 8.1.

For each individual, linear regression analysis was performed between the dependent variables, $\log_{10}(\psi_s)$ and $\log_{10}(\psi_v)$, and the independent variables, L_{Aeq} and $\log_{10}(a_{rms})$. Median and inter-quartile ranges of the exponents, n , the constants, k , and Spearman rank correlation coefficients, r , between ψ and ϕ are shown for the three repetitions in Table 8.1 (individual values are shown in Appendix B). Individual values of the exponents are shown in Figure 8.2 with medians and inter-quartile ranges.

Table 8.1 The exponents (n_v and n_s), the constants (k_v and k_s), and Spearman's rank correlation coefficients (r_v and r_s), obtained with RME and AME methods of magnitude estimation when judging the discomfort of noise and the discomfort of vibration. Medians and inter-quartile ranges for 20 subjects.

Vibration						
Repetition	RME			AME		
	n_{vr}	k_{vr}	r_{vr}	n_{va}	k_{va}	r_{va}
1	0.69 (0.37, 0.81)	263 (178, 309)	0.97 (0.93, 0.98)	0.77 (0.66, 1.02)	302 (257, 417)	0.87 (0.85, 0.91)
2	0.77 (0.45, 0.97)	295 (190, 347)	0.99 (0.96, 0.99)	0.84 (0.68, 1.07)	316 (275, 550)	0.88 (0.82, 0.91)
3	0.81 (0.34, 0.99)	288 (182, 363)	0.98 (0.95, 0.99)	0.81 (0.72, 1.03)	324 (275, 490)	0.85 (0.89, 0.93)
Noise						
Repetition	RME			AME		
	n_{sr}	k_{sr}	r_{sr}	n_{sa}	k_{sa}	r_{sa}
1	0.78 (0.68, 0.96)	0.13 (0.034, 0.35)	0.97 (0.94, 0.98)	0.80 (0.60, 1.08)	0.087 (0.012, 0.58)	0.89 (0.84, 0.92)
2	0.88 (0.68, 1.02)	0.060 (0.020, 0.34)	0.98 (0.97, 0.98)	0.88 (0.60, 1.12)	0.056 (0.0058, 0.60)	0.94 (0.91, 0.96)
3	0.78 (0.64, 1.10)	0.12 (0.010, 0.43)	0.98 (0.97, 0.99)	0.80 (0.62, 1.08)	0.13 (0.087, 0.46)	0.92 (0.86, 0.94)

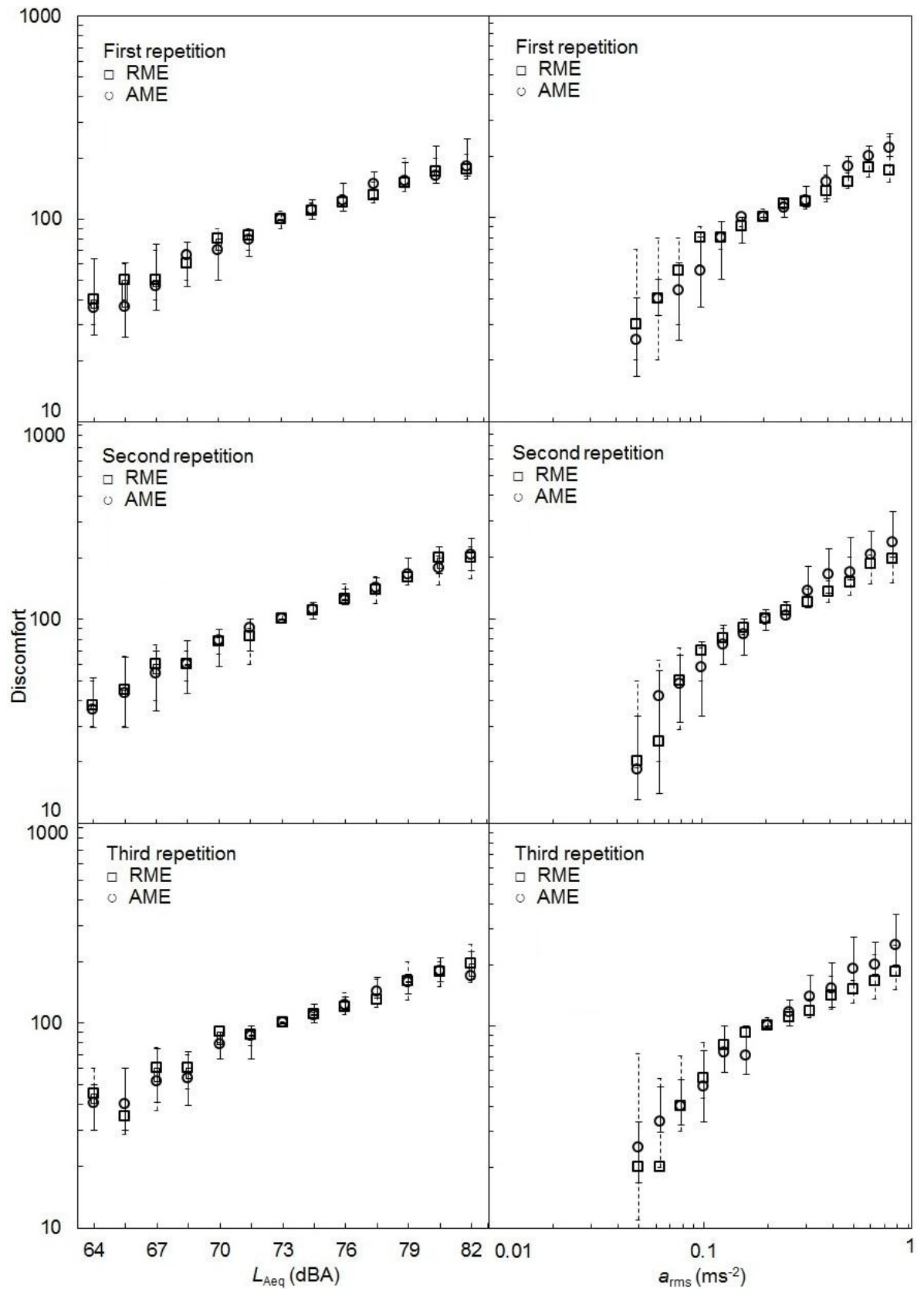


Figure 8.1 Subjective magnitudes of discomfort produced by noise (as a function of L_{Aeq}) or vibration (as a function of a_{rms}) when using the RME and AME magnitude estimation methods. Medians and inter-quartiles ranges of 20 subjects (--○--RME; —□--AME).

Ten subjects attended session A (with AME on vibration and RME on noise) first (Group 1), and the other ten attended session B (with AME on noise and RME on vibration) first (Group 2). There was no significant difference between the exponent obtained by Group 1 and Group 2 using AME (Wilcoxon, $p > 0.02$).

8.3.2 Repeatability within methods

When judging the discomfort produced by vibration using RME, both the exponent, n_{vr} , and the constant, k_{vr} , varied over the three repetitions ($p < 0.02$, Friedman), with a greater exponent and

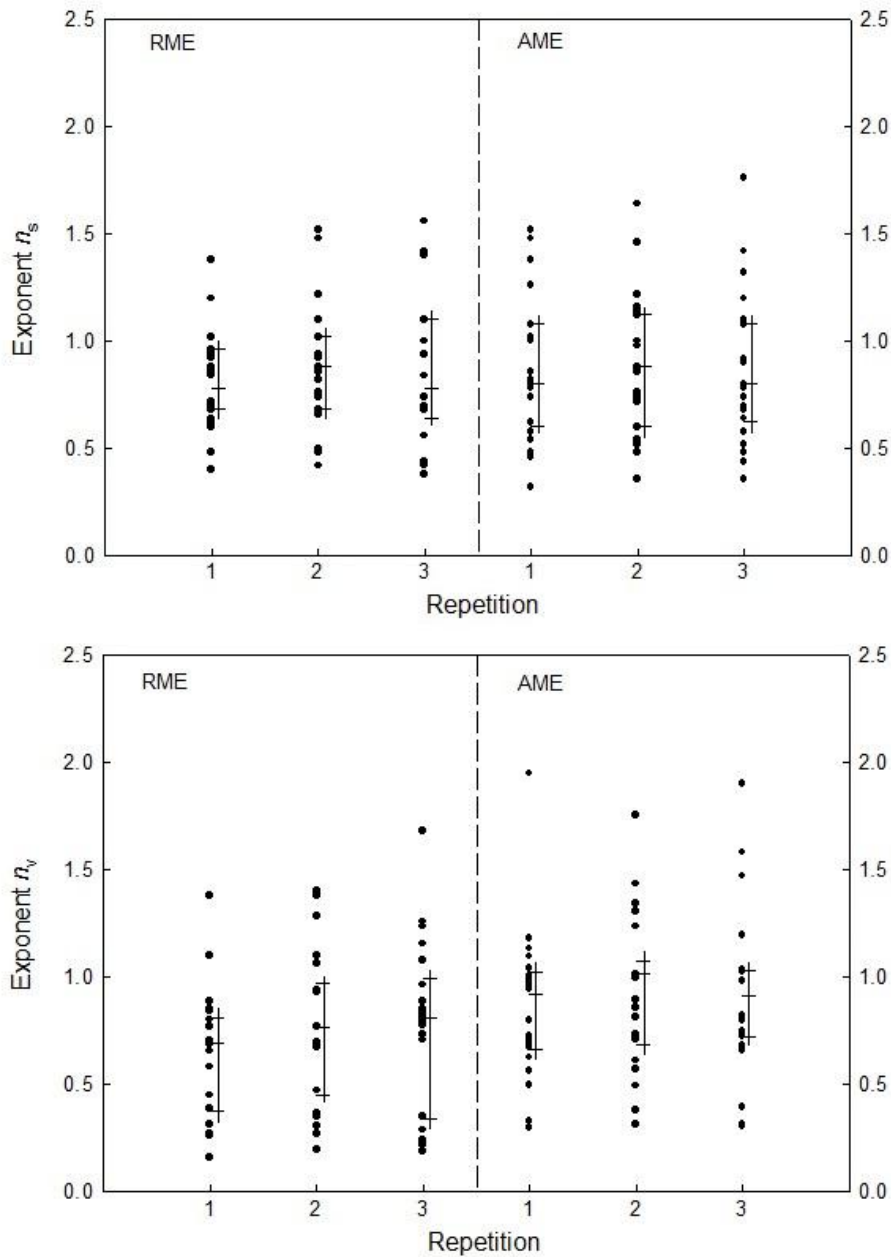


Figure 8.2 Individual exponents of noise, n_s , and vibration, n_v , when using the RME and AME magnitude estimation methods. + Medians and inter-quartiles ranges of 20 subjects.

greater constant for the second repetition than the first repetition ($p < 0.01$, Wilcoxon). Correlation coefficients between magnitude estimates of discomfort and the magnitude of vibration, r_{vr} , also differed over the three repetitions ($p = 0.02$, Friedman; Table 8.1), with significantly higher correlations for the second repetition than the first repetition ($p = 0.02$, Wilcoxon). With AME, there were no statistically significant changes in the exponent, n_{va} , the constant, k_{va} , or the correlation, r_{va} , over the three repetitions ($p = 0.15$ for exponent, $p = 0.71$ for constant, $p = 0.39$ for correlation, Friedman).

When judging the discomfort produced by noise using RME, the exponent, n_{sr} , varied over the three repetitions ($p = 0.04$, Friedman; Table 8.1), but there was no change in either the constant, k_{sr} , or the correlation coefficients between magnitude estimates of discomfort and the level of noise, r_{sr} , over the three repetitions ($p = 0.12$ for constant, $p = 0.29$ for correlation, Friedman). With AME, neither the exponent, n_{sa} , nor the constant, k_{sa} , showed statistically significant changes over the three repetitions ($p = 0.69$ for exponent, $p = 0.95$ for constant, Friedman). The correlations, r_{sa} , differed over the three repetitions ($p = 0.02$, Friedman), with correlations for the second repetition significantly greater than those for the first repetition ($p < 0.02$, Wilcoxon), and the third repetition ($p < 0.05$, Wilcoxon).

There was high consistency in individual judgements across repetitions, as indicated by significant correlations between the exponents, n , and the constants, k , between repetitions 1 and 2, between repetitions 2 and 3, and between repetitions 1 and 3, when judging the discomfort of either vibration or noise when using either RME or AME (in all cases, $p < 0.01$; Table 8.2). Consistency tended to be greater when using the RME method, with 10 of the 12 correlations greater when using RME than when using AME.

8.3.3 Comparison between magnitude estimation methods

When judging the discomfort produced by vibration, the exponent, n_v , was greater with AME than RME during the first repetition ($p = 0.04$, Wilcoxon, Table 8.1), but did not differ between the methods in the second and third repetitions ($p > 0.12$, Wilcoxon, Table 8.1). Over all three repetitions, the constant, k_v , was greater with AME than RME ($p < 0.03$, Wilcoxon; Table 8.1).

When judging the discomfort produced by noise, neither the exponent, n_s , nor the constant, k_s , differed between RME and AME in any repetition (for n_s , $p > 0.19$; for k_s , $p > 0.20$, Wilcoxon; Table 8.1).

The individual correlation coefficients between magnitude estimates of discomfort and either the magnitude of vibration or the level of noise were greater when using RME (i.e., r_{vr} and r_{sr}) than when using AME (i.e., r_{va} and r_{sa}) for all three repetitions ($p < 0.01$, Wilcoxon; Table 8.1).

There was consistency in individual exponents, n , and constants, k , obtained when using RME and AME (Table 8.3). Subjects giving a high value for n or k with one method tended to give a high value with the other method. However, it may be seen that the correlations between repetitions within methods are greater than the correlations between methods within repetitions (compare Tables 8.2 and 8.3).

8.3.4 Independence of the sensations of noise and vibration

Correlations between the exponents, n_s and n_v , obtained by AME and RME are listed in Table 8.4. With both methods, correlations between the exponents tended to increase with increasing repetition and were highly significant for the third repetition (Table 8.4). This indicates that subjects having a high rate of growth of discomfort for noise are likely to have a high rate of growth of discomfort for vibration. At each repetition, the correlations were greater with RME than with AME.

8.4 Discussion

8.4.1 Repeatability of the two methods

All the correlation coefficients between magnitude estimates of discomfort and magnitudes of vibration or noise (i.e., r_{vr} , r_{sr} , r_{va} , r_{sa} ; Table 8.1) have high values, with a tendency towards

Table 8.2 Correlation coefficients between exponents (n_v and n_s) and constants (k_v and k_s) in successive runs when judging the discomfort produced by vibration and the discomfort produced by noise (Spearman rank correlation; 20 subjects).

Vibration							
RME				AME			
n_{vr}	1	2	3	n_{va}	1	2	3
1	1.00	0.84**	0.79**	1	1.00	0.87**	0.87**
2	—	1.00	0.95**	2	—	1.00	0.87**
3	—	—	1.00	3	—	—	1.00
k_{vr}	1	2	3	k_{va}	1	2	3
1	1.00	0.91**	0.92**	1	1.00	0.87**	0.88**
2	—	1.00	0.97**	2	—	1.00	0.93**
3	—	—	1.00	3	—	—	1.00

Noise							
RME				AME			
n_{sr}	1	2	3	n_{sa}	1	2	3
1	1.00	0.95**	0.97**	1	1.00	0.85**	0.86**
2	—	1.00	0.94**	2	—	1.00	0.92**
3	—	—	1.00	3	—	—	1.00
k_{sr}	1	2	3	k_{sa}	1	2	3
1	1.00	0.93**	0.98**	1	1.00	0.85**	0.87**
2	—	1.00	0.93**	2	—	1.00	0.93**
3	—	—	1.00	3	—	—	1.00

** $p < 0.01$.

Table 8.3 Correlations between exponents (n_v and n_s), the constants (k_v and k_s) obtained using RME and AME methods in successive repetitions when judging the discomfort produced by vibration and the discomfort produced by noise. (Spearman rank correlation; 20 subjects).

Vibration							
n_{va} n_{vr}	1	2	3	k_{va} k_{vr}	1	2	3
1	0.48*	—	—	1	0.51*	—	—
2	—	0.50*	—	2	—	0.54*	—
3	—	—	0.56**	3	—	—	0.56*

Noise							
n_{sa} n_{sr}	1	2	3	k_{sa} k_{sr}	1	2	3
1	0.70**	—	—	1	0.71**	—	—
2	—	0.72**	—	2	—	0.72**	—
3	—	—	0.68**	3	—	—	0.72**

* $p < 0.05$, ** $p < 0.01$

Table 8.4 Correlations between exponents, n_v and n_s obtained when judging the discomfort produced by vibration and the discomfort produced by noise when using the RME and the AME method in successive repetitions. (Spearman rank correlation; 20 subjects).

RME				AME			
n_{sr} n_{vr}	1	2	3	n_{sa} n_{va}	1	2	3
1	0.39	—	—	1	0.28	—	—
2	—	0.44	—	2	—	0.32	—
3	—	—	0.68**	3	—	—	0.48*

* $p < 0.05$, ** $p < 0.01$

higher correlations in the second repetition. The high correlations in the exponents, n , and the intercepts, k , across repetitions within both RME and AME suggests a single run would have been sufficient to obtain reasonable estimates of both the exponents and the intercepts (Table 8.2).

Over the three repetitions, the absence of significant changes in the exponents, n , with AME, but significant changes in those obtained by RME, must be interpreted relative to the inter-subject variability in the n values with the two methods (Table 8.1). With inter-subject variability expressed as the ratio of the inter-quartile range to the median value, the variability in the n value of vibration in the first repetition was greater for RME than AME (0.638 compared with 0.468; Table 8.5). Over the three repetitions, the variability in n for vibration increased with RME but reduced with AME. So the significant changes in n for vibration over the three repetitions with RME but not with AME cannot be attributed to greater inter-subject variability with AME.

Table 8.5 The inter-subject variability (ratio of the inter-quartile range to the median value) for the exponents (n_v and n_s) obtained using RME and AME when judging the discomfort of noise and the discomfort of vibration. Data from 20 subjects.

Repetition	Vibration		Noise	
	RME (n_{vr})	AME (n_{va})	RME (n_{sr})	AME (n_{sa})
1	0.638	0.468	0.359	0.600
2	0.675	0.464	0.386	0.591
3	0.802	0.382	0.590	0.575

The variability in the n value of noise in the first repetition was less for RME than for AME (0.359 compared with 0.600; Table 8.5). Over the three repetitions, the variability in n for noise increased with RME but reduced with AME. So the significant change in n for noise over the three repetitions with RME, but not with AME, seems to be associated with inter-subject variability initially being less with RME than with AME.

8.4.2 Comparison of the two methods

The majority of subjects judged RME easier than AME, consistent with higher correlation coefficients between magnitude estimates of discomfort and the magnitude of vibration or the level of noise when using RME (Table 8.1). Over the three repetitions, the exponent for noise, n_s , tended to be more consistent with RME than with AME, whereas the exponent of vibration, n_v , tended to be more consistent with AME than with RME (Table 8.2). The presentation of the reference stimulus with a given sensation (a magnitude estimate of '100') seems to have stabilised magnitude estimates when judging noise, but not when judging vibration.

When judging vibration, the exponent, n_v , differed between the RME and AME methods in the first repetition and the constant, k_v , differed in all three repetitions (Table 8.1). When judging noise, neither the exponent, n_s , nor the constant, k_s , differed between the RME and the AME methods (Table 8.1). Subjects are familiar with the sensations caused by sound and judging the discomfort (or annoyance) of a sound. Subjects are less familiar with the sensations in different parts of the body produced by low, medium, and high magnitudes of vibration. For the familiar stimulus (i.e., noise), subjects provided the same results using RME and AME. For the less familiar stimulus (i.e., vibration), RME provided a significantly lower value of n_v in the first repetition but this increased so that there was no difference between RME and AME in the second and third repetition. The constant, k_v , differed between RME and AME during all repetitions and increased progressively over the three repetitions with both methods (Table 8.3). It seems that with sufficient practice the two methods may provide similar values of n_v and k_v , with practice being more important with RME than AME and n_v stabilising before k_v . The greater practice needed with RME may have arisen because subjects initially tried to match sensations to those produced by the reference motion, but later realised that there were several sensations that change with the magnitude of the vibration (e.g., the locations in the body where discomfort

is felt can vary with the magnitude of vibration). For such a stimulus, an overall judgement of sensation may be more appropriate than trying to match specific sensations.

When judging vibration, the inter-subject variability in n_v (i.e., ratios of inter-quartile ranges to median values) was less with AME than with RME. When judging noise, the inter-subject variability in n_s was less with RME than with AME (Table 8.5). It seems that when judging a specific sensation (i.e., noise), RME had less variability than AME, whereas when judging the various sensations produced by vibration, AME had less variability than RME.

There was greater variability in the magnitude estimates for low magnitudes of vibration with RME than with AME (Figure 8.2: left of right three graphs), consistent with greater inter-subject variability in n_v values with RME than with AME. This is also consistent with greater difficulty when the test vibration is most different from the reference stimulus. Subjects may have had greater difficulty judging low magnitude vibration stimuli that produce sensations that are different from those produced by the reference stimulus, and they may have been more likely to give 'real' subjective magnitudes to the stimuli when using AME without the constraint of the reference (Zwislocki and Goodman, 1980).

8.4.3 The values of n_v and n_s

Various values of the rate of growth of discomfort caused by vibration, n_v , have been reported: between 0.86 and 1.04 for frequencies in the range 3.5 to 20 Hz (Shoenberger and Harris, 1971), 0.93 for frequencies from 5 to 80 Hz (Jones and Saunders, 1974), 1.04 to 1.47 for frequencies from 4 to 63 Hz (Howarth and Griffin, 1988), 1.18 for frequencies of 10 to 50 Hz (Howarth and Griffin, 1991), and 0.626 to 0.897 for frequencies between 2 and 50 Hz (Morioka and Griffin, 2006). In the present study with random vibration in the range 5 to 10 Hz, the median value of 0.77 over three repetitions with RME, and the median value of 0.81 with AME (Table 8.1) seem consistent with Shoenberger and Harris (1971) and Morioka and Griffin (2006) for vibration in the same frequency range.

For sound, an exponent of 0.68 was originally proposed to relate the subjective magnitude of loudness to the sound pressure of 1000-Hz tones by Stevens (1986) and is widely quoted. Other values of the rate of growth of annoyance caused by noise, n_s , have also been reported as 0.72 (Howarth and Griffin, 1991) for 100- to 5000-Hz noise inside a house during the passage of a near-by train, and 0.38 to 0.72 (Huang and Griffin, 2010) for 100- to 300-Hz noise inside a running car. Using category judgment, AME, and cross-modality matching to brightness, with 1000-Hz tone stimuli from 55 to 82 dB, Ward *et al.* (1996) found values of 0.411, 0.483, and 1.017, respectively. In the present study with random noise from 50 to 500 Hz, the median value of 0.78 over three repetitions with RME, and the median value of 0.80 with AME (Table 8.1) are greater than the originally proposed value of 0.68 but within the range of previous values for the exponent, which may be expected to vary with the spectrum of the noise.

8.5 Conclusions

When judging the discomfort produced by noise and vibration, both absolute magnitude estimation (AME) and relative magnitude estimation (RME) provide rates of growth of subjective sensations with high repeatability. When judging noise, RME produced slightly greater consistency with less inter-subject variability in the exponent, n_s , over the three repetitions. When judging vibration, RME was slightly more consistent but had greater variability in the exponent, n_v , over the three repetitions than AME. When judging vibration, AME may be beneficial because, unlike RME, it does not require subjects to judge their sensations relative to the sensations caused by the reference stimulus, which may differ in their nature from the sensations caused by the test stimuli.

Chapter 9 Interaction and combined effects on the discomfort of noise and vibration

9.1 Introduction

People experience vibration and noise in transport and in buildings. Many studies have investigated human reactions to noise (e.g., noise annoyance) or the sensations produced by vibration (e.g., vibration discomfort) and there are separate standards and guides for measuring, evaluating, and assessing noise and vibration with respect to human responses. However, it can be expected that there may be a collective response to a combination of noise and vibration that is greater than the reaction to either noise or vibration alone. A universal model is needed for predicting the discomfort caused by combined noise and vibration.

Some investigations of the combined effects of noise and vibration have assumed the discomfort caused by combined noise and vibration is equivalent to the summated discomfort caused by the two stressors acting separately (e.g., Innocent and Sandover (1972), Dempsey *et al.* (1979), and Leatherwood (1979)). However, some studies suggest a more complex response. Howarth and Griffin (1990, 1991) simulated the noise and vibration in a building near a railway and concluded there might be a complex interaction between the effects of the noise and vibration, and that an approximation to the annoyance produced by combined noise and vibration might be determined from a summation of the effects of the individual stimuli in a multiple linear regression model. Paulsen and Kastka (1995) investigated the subjective intensity and annoyance produced by combined noise and vibration in a flat during the passing of a nearby tram and from the working of a hammermill, and concluded that the combined effects were dominated by the noise but also influenced by the vibration.

There is evidence that judgements of one stimulus (noise or vibration) can be influenced by the presence of the other stimulus (vibration or noise). Sandover (1970), Miwa and Yonekawa (1973) and Huang and Griffin (2012) found an antagonistic (i.e., masking) effect of noise on the sensation of vibration, while Seidel *et al.* (1989, 1990) reported synergistic (i.e., additive) effects of noise on judgements of vibration. Howarth and Griffin (1990, 1991) found both antagonistic and synergistic effects of noise on judgements of vibration, depending on the relative magnitudes of noise and vibration. Dempsey *et al.* (1976) and Kirby *et al.* (1977) also reported evidence of an influence of noise on judgements of vibration discomfort, but did not clearly indicate whether the effects antagonistic or synergistic. Huang and Griffin (2012) suggested antagonistic effects of vibration on judgements of noise discomfort, while Paulsen and Kastka (1995) and Parizet *et al.* (2004) suggested synergistic effects of vibration on, respectively, the annoyance and the discomfort caused by noise.

Effects of noise on judgements of vibration and effects of vibration on judgements of noise have rarely been found in the same study of the interactive and combined effects of noise and vibration. Howarth and Griffin (1990) found significant influences of noise on judgements of

vibration annoyance but noise annoyance was unaffected by simultaneous vibration. In contrast, Paulsen and Kastka (1995) found vibration influenced noise annoyance but noise had a negligible influence on vibration annoyance. The dissimilarity in findings may have arisen from the different magnitudes of the stimuli that were studied: noise in the range 54 to 79 dBA and vibration in the range 0.02 to 0.13 ms^{-2} in the Howarth and Griffin study, but lower levels of noise (30 to 60 dBA) with similar magnitudes of vibration (0.05 to 0.32 mm/s) in the Paulsen and Kastka study. Differences in the frequency spectra of their stimuli, differences in methods, and differences in the phrasing of the questions may also have contributed to the apparently contrary findings. Equations have been proposed in some studies to predict subjective responses ('discomfort' or 'annoyance') to combined noise and vibration (e.g., Dempsey *et al.*, 1979; Howarth and Griffin, 1990, 1991; Paulsen and Kastka, 1995; Seidel *et al.*, 1990) but it is not known whether they apply to a wider range of stimuli.

In general, the findings of previous studies of 'discomfort' (e.g., Sandover, 1970; Miwa and Yonekawa, 1973; and Huang and Griffin, 2012) suggest 'masking effects' of noise on judgements of vibration and 'masking effects' of vibration on judgements of noise when the stimuli are presented simultaneously at noise levels and vibration magnitudes that people feel 'noisy' or 'uncomfortable': sound pressure levels greater than 65 dBA (the daytime level in EU/DG Environment Directive, 2002) or acceleration greater than 0.32 ms^{-2} r.m.s. (British Standards Institute, 1987; International Organization for Standardization, 1997).

For both noise and vibration, when another component of noise or vibration is added, the predicted discomfort is assumed to increase. There are complex methods for predicting the increase in discomfort (e.g., allowing for masking between stimuli) but simple meters for evaluating the severity of noise or vibration stimuli use the root-mean-square of the frequency-weighted stimuli. So the discomfort is not predicted to increase to a value equivalent to the sum of the physical magnitudes of the weighted components in the stimulus but to a value equivalent to the square-root of the sums-of-the-squares of the weighted physical magnitudes of the components in the stimulus. Similarly, the discomfort caused by multi-axis vibration is determined by the root-sums-of-squares (r.s.s.) of the weighted magnitudes in each axis (British Standards Institute, 1987; International Organization for Standardization, 1997). It seems reasonable to investigate how well this 'root-sums-of-squares' method predicts the discomfort caused by combined noise and vibration.

This study was designed to investigate whether noise discomfort is influenced by the presence of vibration, whether vibration discomfort is influenced by the presence of noise, and how the total discomfort from combined noise and vibration can be predicted from the discomfort associated with each stimulus when presented alone. It was hypothesized that: (i) the discomfort, ψ_s , caused by a constant level of noise would reduce with increases in the magnitude of a simultaneous vibration, (ii) the discomfort, ψ_v , caused a constant magnitude of vibration would reduce with increases in the level of a simultaneous noise, (iii) the total discomfort, ψ_c , caused by combined noise and vibration may be predicted from a multiple linear

regression model (i.e., $\psi_c = a + b \psi'_s + c \psi'_v$, where a , b and c are constants, and ψ'_s and ψ'_v represent noise discomfort in the presence of vibration and vibration discomfort in the presence of noise, respectively, and (iv) the total discomfort, ψ_c , can be predicted from the root-sums-of-squares (r.s.s.) of the noise discomfort, ψ_s , and the vibration discomfort, ψ_v , when each stimulus presented alone (i.e., $\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}$).

9.2 Method

9.2.1 Subjects

Twenty-four subjects (12 male and 12 female), with median age 24 years (range 20 to 34 years), stature 170 cm (range 153 to 196 cm), and weight 62 kg (range 42 to 108 kg) volunteered to take part in the experiment. The subjects were students or staff of the University of Southampton.

9.2.2 Stimuli

Seven levels of a random sound, band-pass filtered between 50 and 500 Hz, were generated with sound pressure levels ranging from 64 to 82 dBA in 3 dB steps (ISO 1996-1, 2003). Seven magnitudes of a random vibration, band-pass filtered between 5 and 10 Hz, were generated with frequency-weighted vibration magnitudes from 0.079 to 1.262 ms^{-2} r.m.s. in 2 dB steps (using weighting W_b ; BS 6841, 1987). The sound and vibration stimuli had durations of 4 s, with 0.2-s cosine tapers at the start and end.

For the 4-s stimuli used in the current study, the ratio of the SPL to the SEL was -6 dB, and the ratio of the r.m.s. acceleration to the VDV was 0.51 ($\text{ms}^{-2}/\text{ms}^{-1.75}$).

9.2.3 Procedure

Judgements of 'discomfort' were obtained using the method of absolute magnitude estimation (AME) (Stevens, 1971). The subjects were presented with a series of stimuli and asked to judge the discomfort of the stimuli using any numerical number they felt appropriate.

The experiment was performed in three sessions. In session A, subjects used magnitude estimation to report the discomfort caused by the each of the seven levels of noise in the presence of each of the seven magnitudes of vibration and with no vibration. In Session B, subjects used magnitude estimation to report the discomfort caused by the each of the seven magnitudes of vibration in the presence of each of the seven levels of noise and with no noise. In session C, subjects used magnitude estimation to report the overall discomfort caused by each of the 63 stimuli: 49 combinations of the seven magnitudes of vibration and the seven levels of noise, plus seven levels of noise with no vibration and seven magnitudes of vibration without noise.

Subjects experienced the three sessions on different days and in a balanced order. All stimuli in each session were presented once in an independent random order. Before commencing each session, subjects were provided with written instructions, which indicated they could use any numerical values to rate the subjective magnitudes of the stimuli, but did not indicate any

numerical examples. Subjects then practiced judging the median, high, and low magnitudes stimuli until they felt confident with absolute magnitude estimation.

Magnitude estimates obtained from each individual in each session were divided by the median magnitude estimate over all stimuli in that session and then multiplied by '100' (Stevens, 1971). This 'normalised' (or 'equalised') the data and placed the magnitude estimates of each subject on a similar scale so that they could be compared and analysed using the same procedures.

The Stevens' power equations (Stevens, 1986) are expressed logarithmically as:

$$\log_{10}(\psi_s) = \log_{10}(k_s) + (n_s/20) L_{AE}, \quad (9.1)$$

where k_s is a constant, n_s is the rate of growth in noise discomfort, and $L_{AE} \propto 20 \log(\phi_s)$ is the equivalent continuous A-weighted SEL (International Organization for Standardization, 2003a), and

$$\log_{10}(\psi_v) = \log_{10}(k_v) + n_v \log_{10}(a_{VDV}), \quad (9.2)$$

where k_v is a constant, n_v is the rate of growth in vibration discomfort, and $a_{VDV} \propto \phi_v$ is the W_b -weighted VDV (British Standards Institution, 1987; International Organization for Standardization, 1997).

9.3 Results

9.3.1 Discomfort of noise in the presence of vibration

Median magnitude estimates of the discomfort produced by each of the seven levels of noise during simultaneous presentation of each of the seven magnitudes of vibration, and with no vibration, are shown in Table 9.1. They are also shown in Figure 9.1 as a function of noise level, L_{AE} , and as a function of vibration magnitude, a_{VDV} . Linear regression between the median values of $\log_{10}(\psi_s)$ and L_{AE} using Equation (9.1) produced the slopes, intercepts, and the coefficients of correlation between the logarithms of the magnitude estimates of noise discomfort (i.e., $\log_{10}(\psi_s)$) and the sound exposure levels (i.e., L_{AE}) at each magnitude of vibration, as shown in Table 9.1.

When the same procedure was applied to the magnitude estimates provided by each subject, it was found that at each noise level, the presence of vibration had no significant effect on the judgement of the discomfort produced by the noise ($p > 0.23$; Friedman).

Without vibration, the rate of growth in discomfort produced by noise (i.e., the slope $n_s/20$ in Equation (9.2)) was 0.036 with an intercept (i.e., $\log_{10}(k_s)$) of -0.792. With simultaneous vibration, the median slopes varied from 0.037 to 0.045 and the intercepts varied from -0.523 to -0.898, but with no significant difference between the slopes or between the intercepts due to variations in the magnitude of vibration ($p = 0.49$; Friedman).

Table 9.1 Magnitude estimates for the discomfort caused by noise, ψ_s (with V_0) and ψ'_s (with V_1 - V_7) and linear regression analysis showing the relation between the subjective magnitude, $\log_{10}(\psi_s)$, and the SEL, L_{AE} , in the presence of different magnitudes of simultaneous vibration. Medians of 24 subjects.

		$a_{VDV}(\text{ms}^{-1.75})$								
LAE (dBA)		V_0	V_1	V_2	V_3	V_4	V_5	V_6	V_7	
		0	0.146	0.230	0.363	0.573	0.906	1.431	2.318	
		ψ_s	ψ'_s	ψ'_s	ψ'_s	ψ'_s	ψ'_s	ψ'_s	ψ'_s	
	N_1	70	48.5	40.4	34.9	44.6	43.8	40.0	41.5	46.1
	N_2	73	60.8	60.6	50.0	60.8	55.6	61.0	73.9	56.4
	N_3	76	92.9	79.3	100.0	82.8	83.0	80.6	81.2	68.3
	N_4	79	105.2	114.0	111.7	107.5	107.5	100.0	120.1	102.6
	N_5	82	147.7	141.4	150.0	150.6	137.3	148.7	138.1	148.7
	N_6	85	166.7	178.4	195.2	175.0	185.7	194.7	178.6	195.2
N_7	88	211.5	213.0	220.2	210.8	225.8	222.5	210.0	235.7	
a_{VDV} ($\text{ms}^{-1.75}$)		Slope ($n_s/20$)		Intercept ($\log_{10}(k_s)$) (dB)			Correlation (r_s)			
0		0.036		-0.792			0.991			
0.146		0.040		-1.144			0.992			
0.230		0.045		-1.523			0.973			
0.363		0.038		-0.994			0.994			
0.573		0.041		-1.187			0.997			
0.906		0.042		-1.287			0.993			
1.431		0.037		-0.898			0.980			
2.318		0.042		-1.318			0.994			

Equivalent continuous SPL, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

9.3.2 Discomfort of vibration in the presence of noise

Median magnitude estimates of the discomfort produced by each of the seven magnitudes of vibration when presented simultaneously with each of the seven levels of noise, and with no noise, are shown in Table 9.2. They are also shown in Figure 9.2 as a function of noise level, L_{AE} , and as a function of vibration magnitude, a_{VDV} . Linear regression analyses between the median values of $\log_{10}(\psi_v)$ and $\log_{10}(a_{VDV})$ using Equation (9.2) produced the slopes, intercepts, and the coefficients of correlation between the logarithms of the magnitude estimates of vibration discomfort (i.e., $\log_{10}(\psi_v)$) and the logarithms of the vibration dose values (i.e., $\log_{10}(a_{VDV})$) at each level of noise, as shown in Table 9.2.

The upper part of Figure 9.2 shows a trend for the presence of noise to reduce the discomfort caused by vibration and, together with Table 9.2 suggests a 'masking effect' of noise on judgements of vibration discomfort that increases with increasing levels of noise. However, the statistical analyses on the individual magnitude estimates show that, after Bonferroni correction (Shaffer, 1995), at each vibration magnitude, the noise had no significant effects on the judgement of the discomfort produced by vibration (corrected $p > 0.05$; Friedman).

Table 9.2 Magnitude estimates for the discomfort caused by vibration, ψ_v (with N_0) and ψ'_v (with N_1 - N_7) and linear regression analysis showing the relation between the subjective magnitude, $\log_{10}(\psi_v)$, and the VDV, a_{VDV} , in the presence of different levels of simultaneous noise. Medians of 24 subjects.

$L_{AE}(\text{dBA})$									
a_{VDV} ($\text{ms}^{-1.75}$)		N_0	N_1	N_2	N_3	N_4	N_5	N_6	N_7
		0	70	73	76	79	82	85	88
		ψ_v	ψ'_v	ψ'_v	ψ'_v	ψ'_v	ψ'_v	ψ'_v	ψ'_v
	V_1	32	30	36.7	32.1	27.9	28.6	25	27.9
	V_2	48.5	50	50	46.6	50	50	46.4	41.4
	V_3	75	73.9	95	75	90	86.7	100	71.7
	V_4	134.9	107.9	117.1	118.7	129.2	116.0	116.0	100
	V_5	190.9	169.1	179.2	175.7	200	200	204.4	200
	V_6	273.3	265	250	245	262.8	300	281.7	300
	V_7	339.3	358.6	331.0	368.6	373.5	378.6	369.3	321.3
L_{AE} (dBA)		Slope (n_v) ($1/(\text{ms}^{-1.75})$)		Intercept ($\log_{10}(k_v)$)			Correlation (r_v^2)		
0		0.891		2.277			0.984		
70		0.902		2.257			0.998		
73		0.812		2.263			0.993		
76		0.893		2.260			0.999		
79		0.924		2.293			0.991		
82		0.945		2.300			0.994		
85		0.963		2.296			0.984		
88		0.957		2.258			0.988		

Equivalent continuous SPL, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

Linear regression analyses between $\log_{10}(\psi_v)$ and $\log_{10}(a_{VDV})$ using Equation (6) were applied to the magnitude estimates provided by each subject. Without noise, the rate of growth in vibration discomfort (i.e., the slope n_v in Equation (9.2)) was 0.891 with an intercept (i.e., $\log_{10}(k_v)$) of 2.277. With simultaneous noise, the median slopes tended to increase from 0.812 to 0.963, except for the slope of 0.902 with noise at 70 dBA SEL ($p < 0.01$; Friedman), and the intercepts varied from 2.257 to 2.300, but with no significant difference between the intercepts due to variations in the level of noise.

9.3.3 Discomfort of combined noise and vibration

9.3.3.1 General results

Median magnitude estimates of the discomfort produced by all combinations of the seven magnitudes of vibration and the seven levels of noise are shown in Table 9.3. They are illustrated in Figure 9.3 as a function of noise level, L_{AE} , and as a function of vibration magnitude, a_{VDV} .

Linear regression between median values of $\log_{10}(\psi_v)$ and L_{AE} when judging noise without vibration produced a rate of growth in noise discomfort (i.e., the slope $n_s/20$ in Equation (9.1)) of

0.035 with an intercept (i.e., $\log_{10}(k_s)$) of -0.923 with a correlation coefficient of 0.99 ($p < 0.01$, Spearman):

$$\log_{10}(\psi_s) = -0.923 + 0.035 L_{AE}. \quad (9.3)$$

Linear regression between the median values of $\log_{10}(\psi_c)$ and $\log_{10}(a_{VDV})$ judging vibration without noise, produced a rate of growth in vibration discomfort (i.e., the slope n_v in Equation (9.2)) of 0.947 with an intercept (i.e., $\log_{10}(k_v)$) of 1.852 with a correlation coefficient of 0.99 ($p < 0.01$, Spearman):

$$\log_{10}(\psi_v) = 1.852 + 0.947 \log_{10}(a_{VDV}). \quad (9.4)$$

When the same procedures were applied to the magnitude estimates provided by each subject, the total discomfort increased as the noise level increased at each vibration magnitude, and as the vibration magnitude increased at each noise level ($p < 0.001$; Friedman). There was no significant difference in the slope (i.e., $n_s/20$), or the intercept (i.e., $\log_{10}(k_s)$) between session C (discomfort with combined noise and vibration) and session A (noise discomfort) when judging noise discomfort without vibration ($p = 0.07$ for slope, and $p = 0.24$ for intercept; Wilcoxon). There was no significant difference in the slope (i.e., n_v) between session C (discomfort with combined noise and vibration) and session B (vibration discomfort) but a smaller intercept (i.e., $\log_{10}(k_v)$) in session C than in session B when judging vibration discomfort without noise ($p = 0.14$ for slope, and $p < 0.001$ for intercept; Wilcoxon).

9.3.3.2 Multiple linear regression model

Assume the discomfort caused by combined noise and vibration, ψ_c can be predicted by:

$$\psi_c = a + b \psi'_s + c \psi'_v, \quad (9.5)$$

where a , b and c are constants, and ψ'_s and ψ'_v represent the discomfort caused by noise in the presence of vibration and the discomfort caused by vibration in the presence of noise, respectively.

The median magnitude estimates at each combination of the seven levels of noise (70 to 88 dBA) and the seven magnitudes of vibration (0.146 to 2.318 $\text{ms}^{-1.75}$) were obtained from judgements of the discomfort caused by noise in the presence of vibration (i.e., ψ'_s in Table 9.1), the discomfort caused by vibration in the presence of noise (i.e., ψ'_v in Table 9.2), and the discomfort caused by combined noise and vibration (i.e., ψ_c in Table 9.3). These values were used to obtain by multiple linear regressing the relation between the dependent variable, ψ_c , and the two independent variables, ψ'_s and ψ'_v :

$$\psi_c = 18.46 + 0.47 \psi'_s + 0.20 \psi'_v. \quad (9.6)$$

The correlation coefficient for this multiple regression was 0.96 ($p < 0.01$; Spearman).

Table 9.3 Subjective magnitudes for the discomfort caused by combined noise and vibration, ψ_c . Medians of 24 subjects.

		$a_{VDV} \text{ (ms}^{-1.75}\text{)}$							
$L_{AE} \text{ (dBA)}$		V_0	V_1	V_2	V_3	V_4	V_5	V_6	V_7
		0	0.146	0.230	0.363	0.573	0.906	1.431	2.318
	N_0 0	0	11.3	14.6	30.4	49.2	68.6	107.9	131.2
	N_1 70	30.6	39.7	38.2	46.9	51.9	76.5	100	140.6
	N_2 73	42.9	46.4	60	55.4	61.4	80	108.1	143.2
	N_3 76	65.2	66.7	61.8	60	77.6	94.7	117.1	142.9
	N_4 79	76.0	72.8	73.2	85.7	96.9	100	118.4	149.6
	N_5 82	92.8	100	110.6	111.4	112.7	108.3	123.1	158.6
	N_6 85	116.2	112.2	121.5	119.1	129.6	140	158.6	171.9
	N_7 88	134.9	153.1	150	145.1	163.6	155.8	161.8	192.1

Equivalent continuous SPL, $L_{Aeq} = L_{AE} - 6$; r.m.s. acceleration, $a_{rms} = 0.51 \times a_{VDV}$.

9.3.3.3 The root-sum-of-squares model

The magnitude estimates for discomfort produced by combined noise and vibration, ψ_c , for the 49 combinations of noise and vibration (seven levels of noise combined with each of seven magnitudes of vibration) were predicted from the median magnitude estimates of the discomfort caused by the seven levels of noise without vibration, ψ_s , in Table 9.3, and the median magnitude estimates of the seven magnitudes of vibration without noise, ψ_v , in Table 9.3, using:

$$\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}. \quad (9.7)$$

The median measured values of ψ_c in Table 9.3 are compared with the predicted values in Figure 9.4. The correlation coefficient between the measured and the predicted values was 0.99 ($p < 0.01$; Spearman), greater than that of Equation (9.6).

The predictions did not improve by using the discomfort caused by noise in the presence of vibration (i.e., the appropriate value of ψ'_s in Table 9.1) and the discomfort caused by vibration in the presence of noise (i.e., the appropriate value of ψ'_v in Table 9.2): the correlation between the measured and predicted values reduced to 0.89 ($p < 0.01$; Spearman).

9.4 Discussion

9.4.1 Influence of vibration on the discomfort of noise

From Table 9.1, when noise stimuli were presented without vibration, the slope (i.e., $n_s/20$) of 0.036 was similar to Stevens' proposed value of 0.033 (Stevens, 1986). When noise was presented with simultaneous vibration (from 0.146 to 2.318 $\text{ms}^{-1.75}$), the slope was in the range 0.037 to 0.045 (Table I), but not significantly dependent on the vibration magnitude. In a previous study, when the magnitude of the simultaneous vibration increased from 0.092 to 1.457 $\text{ms}^{-1.75}$, the slopes increased from 0.022 to 0.028, consistent with a 'masking effect' of high magnitude vibration on the discomfort caused by low levels of noise (Huang and Griffin, 2012). Relative magnitude estimation (RME) was employed in that study, with subjects judging noise discomfort relative to vibration discomfort, whereas absolute magnitude estimation (AME)

was employed in present study, with subjects giving the numerical values of noise discomfort without a reference.

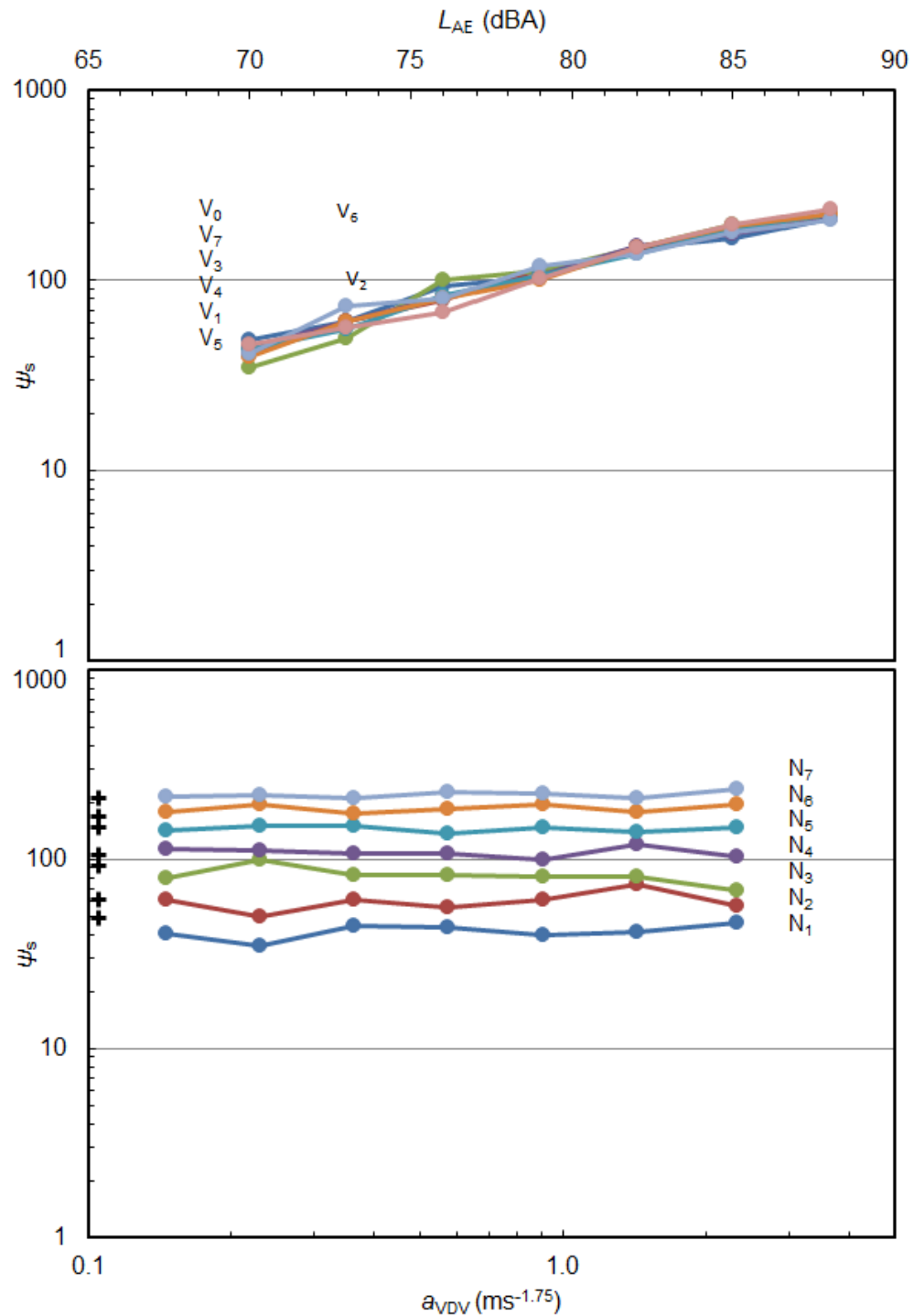


Figure 9.1 Subjective magnitudes of discomfort caused by different levels of noise as a function of SEL (upper) and as a function of VDV (lower). + = no vibration stimuli.

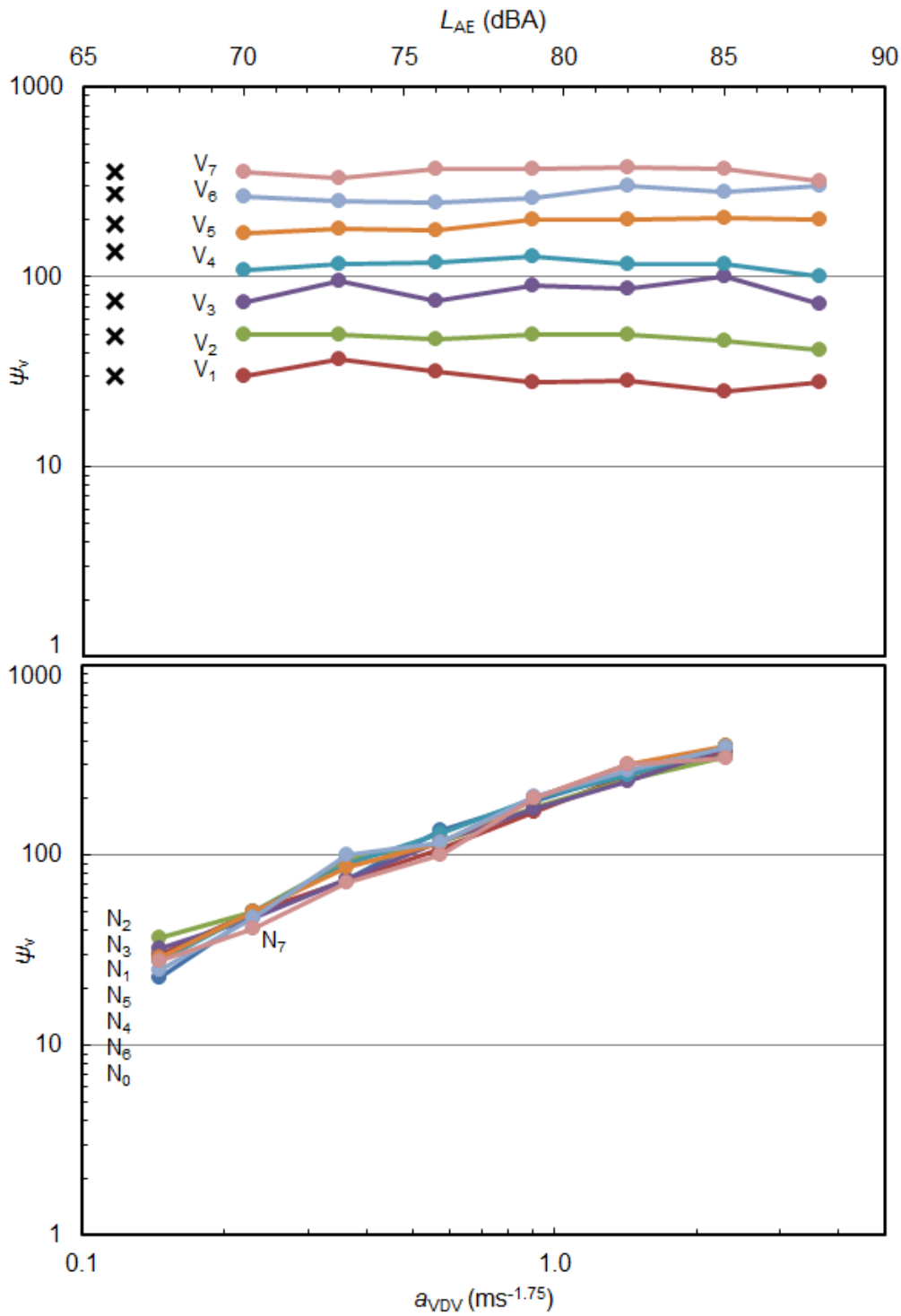


Figure 9.2 Subjective magnitudes of discomfort caused by different magnitudes of vibration as a function of SEL (upper) and as a function of VDV (lower). x = no noise stimuli.

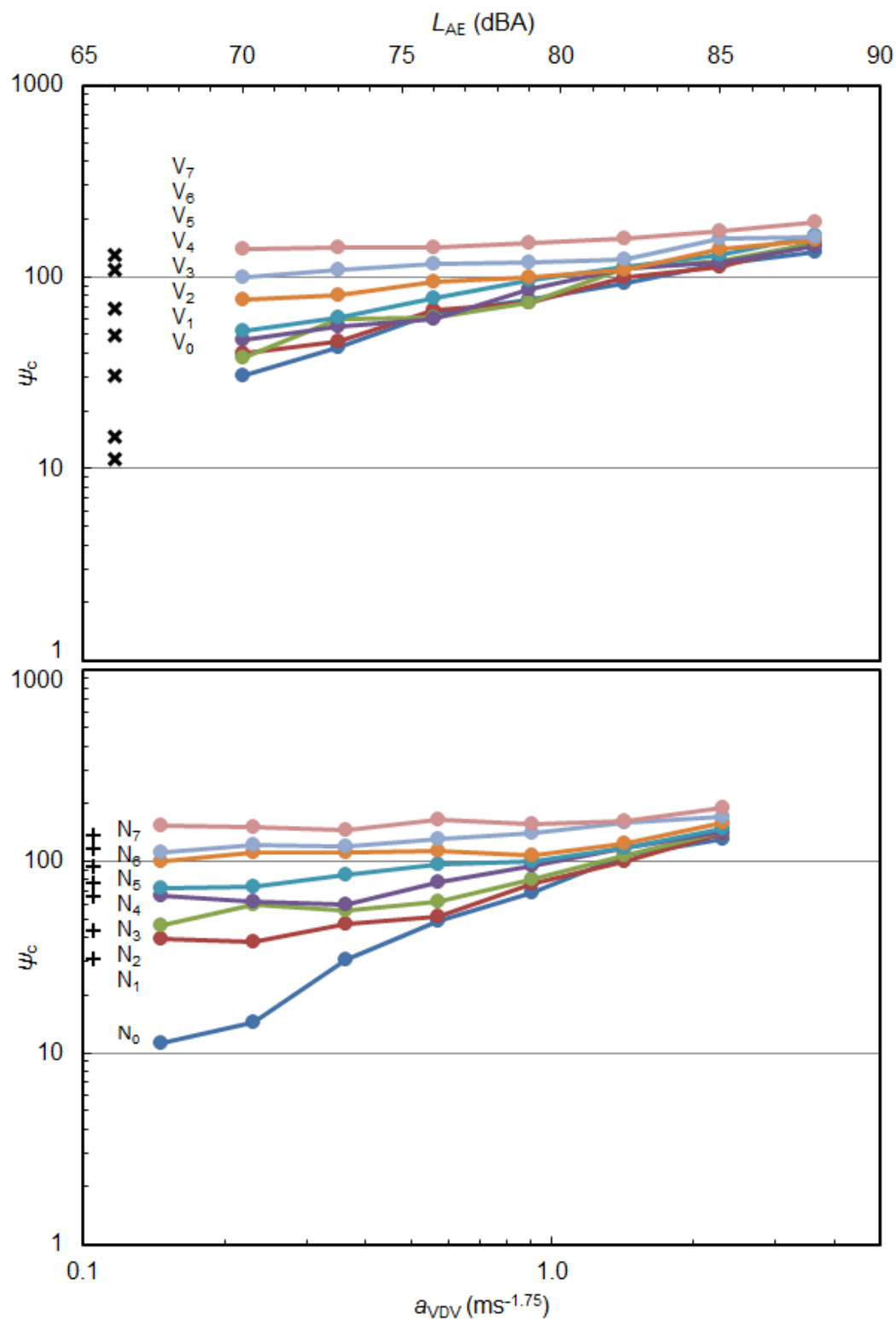


Figure 9.3 The discomfort of combined noise and vibration as a function of SEL (above) and a function of VDV (below). x = no noise stimuli; + = no vibration stimuli.

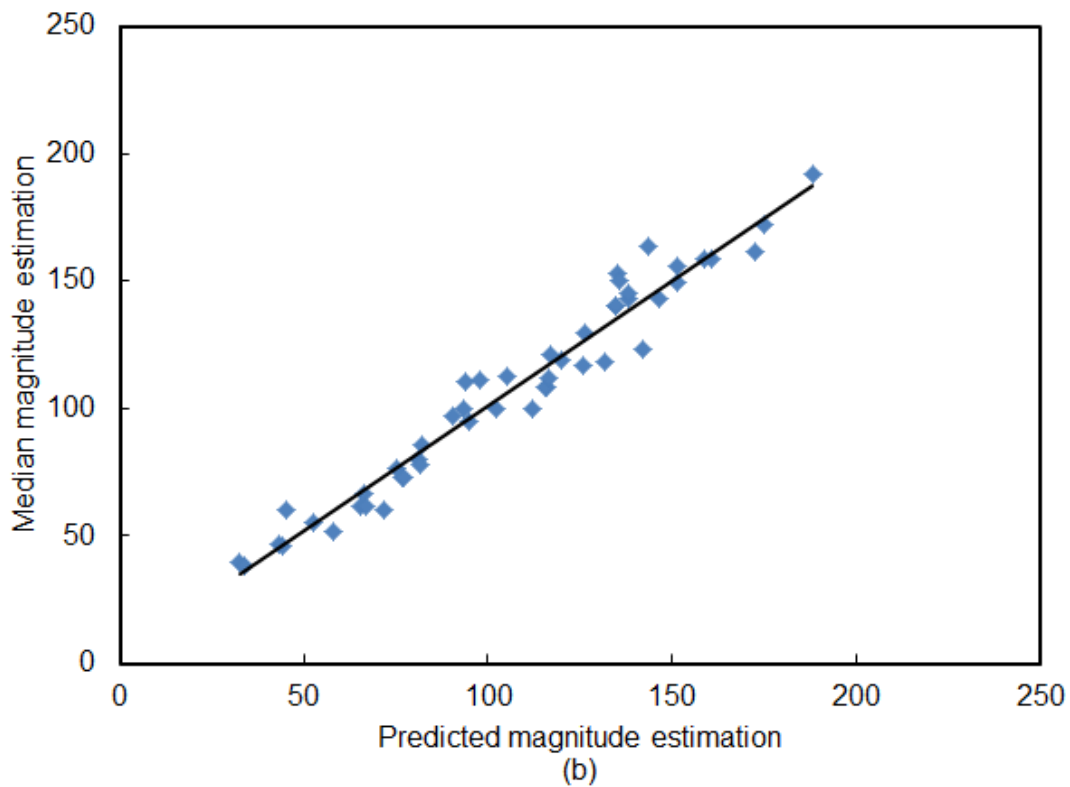
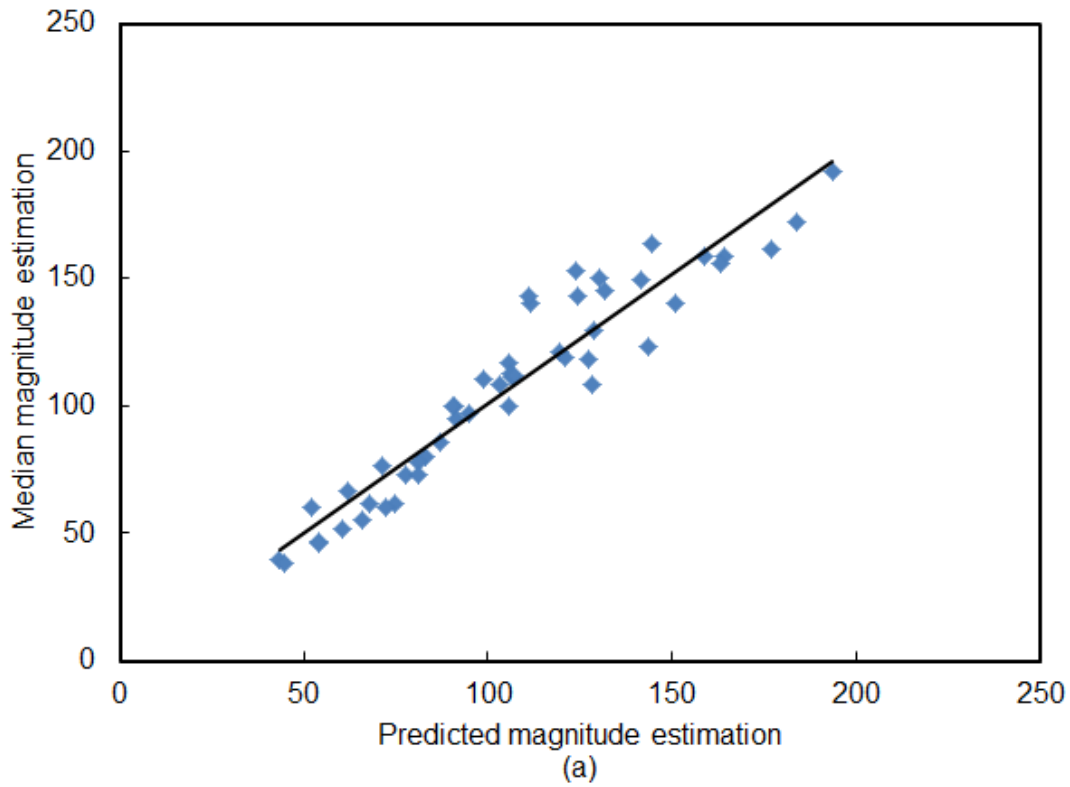


Figure 9.4 Comparison of median magnitude estimates with predicted magnitude estimates of: (a) the multiple linear regression equation, and (b) the root-sum-of-squares model.

The absence of a statistically significant effect of vibration on the slopes in the present study, unlike Huang and Griffin (2012), might be explained if there was a more variable response associated with AME than RME (Mellers, 1983). However, when noise was presented with different magnitudes of vibration, the inter-subject variability (ratio of the inter-quartile range to the median value) in the slopes was in the range 0.41 to 0.64 with AME in the present study, which is not greater than the range 0.49 to 0.93 with RME in the previous study.

Any ‘masking effect’ of vibration on judgements of noise discomfort may have been magnified with RME (a cross-modality procedure in which noise is judged relative to vibration) because vibration was emphasized by employing it as a reference. In the previous study with RME, when the greatest magnitude of vibration ($1.457 \text{ ms}^{-1.75}$) was employed as a reference, the median noise discomfort was ‘35’ for the lowest noise level (70 dBA), and ‘110’ for the highest noise level (88 dBA). In the present study with AME, when presented with a similar magnitude of vibration ($1.431 \text{ ms}^{-1.75}$), the median noise discomfort was ‘42’ for the lowest noise level (70 dBA) and ‘210’ for the highest noise level (88 dBA). It seems the ‘masking effect’ (informational masking) of vibration on judgements of noise discomfort is dependent on the psychophysical method, being greater with RME when noise discomfort is judged relative to a reference magnitude of vibration than with AME.

The slopes obtained previously (Huang and Griffin, 2012) were less than in the present study, possibly due to what Stevens and Greenbaum (1966) called the ‘regression effect’ and Poulton (1979) called the ‘contraction bias’ causing overestimation of the discomfort caused by low magnitude stimuli and underestimation of the discomfort caused by high magnitude stimuli. By not using numerical prompts in the AME instructions (e.g., ‘100’ for the discomfort caused by the reference when using RME) subjects are less likely to locate their ratings at the centre of the range, thus reducing the regression effect. For example, when using the median magnitude of vibration ($0.366 \text{ ms}^{-1.75}$) as a reference to define a discomfort magnitude estimate of ‘100’ in the previous study with RME, the median discomfort caused by seven levels of noise ranged from ‘85’ to ‘200’, whereas when presented with a similar magnitude of vibration ($0.363 \text{ ms}^{-1.75}$) in the present study, the discomfort caused by the same seven levels of noise ranged from ‘45’ to ‘211’.

From Table 9.1, for the discomfort caused by noise without vibration, the relation between the subjective magnitude, ψ_s , and the SEL, L_{AE} , is given by:

$$\log_{10}(\psi_s) = -0.792 + 0.036 L_{AE}. \quad (9.8)$$

With no significant effect of vibration on either the slope or the intercept in Equation (9.1), for the discomfort caused by noise with simultaneous vibration, the linear regression between $\log_{10}(\psi'_s)$ and L_{AE} is given by using the average slope and intercept in Table 9.1:

$$\log_{10}(\psi'_s) = -1.193 + 0.041 L_{AE}. \quad (9.9)$$

With vibration at magnitudes up to $2.318 \text{ ms}^{-1.75}$, this predicts the magnitude of discomfort caused by noise in the presence of vibration (i.e., ψ'_s) to within 16.1% for noise stimuli over the range 70 to 88 dBA.

9.4.2 Influence of noise on the discomfort of vibration

From Table 9.2, when the 5-10 Hz vibration stimuli were presented without noise, the slope (i.e., n_v) of 0.973 is in broad agreement with rates of growth of subjective sensations reported previously (e.g., 1.04 for 5-Hz vibration by Shoenberger and Harris (1971), 0.93 for sinusoidal vibration from 5 to 80 Hz by Jones and Saunders, (1974), 1.04, 1.06, and 1.09 for 4-, 8- and 11.3-Hz vibration by Howarth and Griffin (1988), and 1.04 for vibration in buildings with spectra from 18 to 60 Hz due to the passage of nearby trains by Howarth and Griffin (1990)).

When the vibration stimuli were presented with simultaneous noise (at levels from 70 to 88 dBA), the slope varied and showed some evidence of a slight increase (Table 9.2). In a previous study, when the level of a simultaneous reference noise increased from 70 to 88 dBA, the slope increased from 0.397 to 0.928 (Huang and Griffin, 2012). Similar to the discussion in Section IV.A, the reduced slope in the previous study might have been caused by the 'regression effect' when using the RME method.

Noise has been found to reduce magnitude estimates of discomfort for low magnitude vibration when judging vibration relative to noise using RME (Huang and Griffin, 2012). There may be some evidence of a similar effect of noise on the judgement of vibration discomfort in the present study with AME, but it is much less obvious than in Huang and Griffin (2012). In the previous study with RME, when the highest level of noise (88 dBA) was employed as a reference, the median value of relative vibration discomfort was '10' for the lowest magnitude of vibration ($0.092 \text{ ms}^{-1.75}$), and '100' for the greatest magnitude of vibration ($1.458 \text{ ms}^{-1.75}$), whereas in the present study with AME, when presented with the same level of noise (88 dBA) the median value of vibration discomfort was '28' for the lowest magnitude of vibration ($0.146 \text{ ms}^{-1.75}$), and '321' for the greatest magnitude of vibration ($2.318 \text{ ms}^{-1.75}$). It seems the 'masking effect' of noise on judgements of vibration discomfort is dependent on the psychophysical method, being greater with RME when vibration discomfort is judged relative to a reference level of noise.

The less obvious effect of noise on the slopes in the present study than in Huang and Griffin (2012), cannot be explained by more variable responses with AME than RME (Mellers, 1983). Similar to judgements of noise discomfort, when vibration was presented with different levels of noise, the inter-subject variability (ratio of the inter-quartile range to the median value) in the slopes was in the range 0.35 to 0.54 with AME in the present study, which is not greater than the range 0.35 to 0.76 with RME in the previous study.

Noise has previously been reported to reduce judgements of vibration discomfort by Sandover (1970), Miwa and Yonekawa (1973), and Howarth and Griffin (1990). A synergistic effect of high levels of noise on the annoyance caused by high magnitudes of vibration was found by Howarth

and Griffin (1990) but not observed in the present study, possibly because of the different ranges of stimuli employed in the two studies: Howarth and Griffin (1990) investigated lower levels of noise (40 to 65 dBA SPL) and lower magnitudes of vibration (0.02 to 0.125 ms⁻² r.m.s.) than the present study (SPL from 64 to 82 dBA and r.m.s. acceleration from 0.079 to 1.262 ms⁻²).

From Table 9.2, for the discomfort caused by vibration without noise, the relation between the subjective magnitude, ψ_v , and the VDV, a_{VDV} , is given by:

$$\log_{10}(\psi_v) = 2.277 + 0.891 \log_{10}(a_{VDV}), \quad (9.10)$$

For the discomfort caused by vibration in the presence of noise, there was no significant change in the intercept (i.e., $\log_{10}(k_v)$), and a slight change in the slope (i.e., n_v) in Equation (9.2), so the average slope and intercept in the linear regression between $\log_{10}(\psi'_v)$ and a_{VDV} in Table II might be used:

$$\log_{10}(\psi'_v) = 2.275 + 0.914 \log_{10}(a_{VDV}), \quad (9.11)$$

With noise at levels up to 88 dBA, this predicts the magnitude of discomfort caused by vibration in the presence of noise (i.e., ψ'_s) to within 15.5% for vibration stimuli over the range 0.146 to 2.318 ms^{-1.75}.

9.4.3 The discomfort of combined noise and vibration

9.4.3.1 Range of discomfort magnitudes

From Tables 9.1 to 9.3, the ranges of median magnitude estimates of discomfort were from 35 to 236, with a ratio of 1:7 for ψ_s (and ψ'_s) in session A (noise discomfort), from 23 to 379 with a ratio of 1:16 for ψ_v (and ψ'_v) in session B (vibration discomfort), and from 11 to 192 with a ratio of 1:17 for ψ_c in session C (discomfort with combined noise and vibration).

The range of magnitude estimates for discomfort caused by combinations of noise and vibration (i.e., ψ_c) was greater than that for noise discomfort (i.e., ψ_s (and ψ'_s)) and greater than for vibration discomfort (i.e., ψ_v (and ψ'_v)), but not as great as the sum of the ranges of noise discomfort and vibration discomfort). This might be explained by a 'response equalizing bias' and a 'transfer bias' from ratio scales to interval scales (Poulton, 1979). The response equalizing bias means subjects tend to use the same range of numbers whatever the range of stimuli, so subjects might intentionally or unintentionally give smaller magnitude estimates for the discomfort caused by the combination of two stimuli in session C (discomfort with combined noise and vibration) than the discomfort caused by single stimuli in session A (noise discomfort) and session B (vibration discomfort), so as to avoid the summation of the discomfort exceeding their psychological ranges. The transfer bias in the present experiment comes from transferring ratio scales to interval scales. Subjects used ratio scales to rate noise discomfort and vibration discomfort, but to estimate their total discomfort they may have used interval scales to summate noise discomfort and vibration discomfort. The transfer bias from the ratio scales to an interval

scale may have reduced the range of ψ_c because ratio scales are usually greater than interval scales.

9.4.3.2 *The effect of noise (or vibration) on the subjective judgements of vibration (or noise)*

A ‘masking effect’ of noise on judgements of vibration discomfort was observed in the present study and in some previous studies (e.g., Sandover, 1970; Miwa and Yonekawa, 1973; Howarth and Griffin, 1990; Huang and Griffin, 2012). A ‘masking effect’ of vibration on judgements of noise discomfort was not observed in the present study, possibly due to the relatively higher levels of the noise stimuli (70 to 88 dBA) than the magnitudes of the vibration stimuli (0.146 to 2.318 $\text{ms}^{-1.75}$) (i.e., the noise stimuli produced relatively greater discomfort than the vibration stimuli). Similarly, some previous studies with relatively high levels of noise and low magnitudes of vibration (e.g., Dempsey *et al.* (1976) with SPLs from 70 to 85 dBA and r.m.s. accelerations from 0.3 to 1.2 ms^{-2} , Howarth and Griffin (1990) with SPLs from 40 to 65 dBA and r.m.s. accelerations from 0.02 to 0.125 ms^{-2} , and Seidel *et al.* (1990) with SPLs from 65 to 85 dBA and r.m.s. accelerations from 0.55 to 2.2 ms^{-2}) also found no significant influence of vibration on judgements of noise discomfort. Paulsen and Kastka (1995) employed relatively low levels of noise (32 to 60 dBA SPL) and high magnitudes of vibration (0.05 to 0.32 mm/s) and found the highest magnitude of vibration had a small but significant influence on judgements of noise. It may be presumed that an antagonistic effect of vibration on noise discomfort will be observed if much lower levels of noise or much greater magnitudes of vibration are employed than in the present study.

9.4.3.3 *The predicting models*

A multiple regression model and a root-sums-of-squares (r.s.s.) model were proposed in Section 9.3.3 to predict the discomfort caused by combined noise and vibration from the discomfort caused by noise and the discomfort caused by vibration. From Equation (9.6) and Figure 9.4(a), the multiple regression process was able to provide a reasonably accurate prediction. However, the multiple regression equation might not be applicable when the magnitudes of stimuli exceed the ranges investigated (i.e., 70 to 88 dBA SEL and 0.146 to 2.318 $\text{ms}^{-1.75}$ VDV), or when the physical characteristics of the stimuli (e.g., the frequency spectra of noise and vibration, the direction of vibration) differ from those investigated. The prediction equations in previous studies (e.g., Dempsey *et al.*, 1979; Leatherwood, 1979; Howarth and Griffin, 1990a, 1991; Paulsen and Kastka, 1995; Seidel *et al.*, 1990) have similar limitations and, additionally, they require subjective judgements of each of the stimuli in the presence of all the other stimuli.

Equation (9.7) suggests the subjective magnitude of the discomfort caused by combined noise and vibration can be well predicted by the root-sums-of-squares (r.s.s.) of the subjective magnitude of the noise discomfort and the subjective magnitude of the vibration discomfort. This gave a better prediction of the combined discomfort than the multiple regression equation (i.e., Equation (9.6)), as shown in Figure 9.4. The r.s.s. model implies an interaction between noise and vibration in the subjective judgements: the relative contribution to the total discomfort

caused by either stimulus (noise or vibration) reduces as the magnitude of the other stimulus (vibration or noise) increases. When either stimulus (noise or vibration) has a high magnitude and the other stimulus (vibration or noise) has a low magnitude, the total discomfort will be dominated by the higher magnitude stimulus. The ‘masking effect’ in the r.s.s. model is symmetrical whereas only the ‘masking’ of noise on the vibration discomfort was observed in the present study. When a noise and a vibration produce similar discomfort, it seems more likely that judgements of vibration discomfort are ‘masked’ by noise than judgements of noise discomfort are ‘masked’ by vibration. However, noise discomfort may be masked by vibration if lower levels of noise or greater magnitudes of vibration are employed. When vibration and noise that produce similar discomfort are presented simultaneously, the total discomfort is greater than the discomfort caused by either stimulus alone (about 41% greater due to the squaring and square root procedure), and much less than the sum of the magnitude estimates of discomfort caused by each stimuli alone.

9.4.3.4 Application of the r.s.s. model

To predict the discomfort caused by combined noise and vibration from Equation (9.7) it is necessary to first calculate the discomfort caused separately by the noise component and the vibration component. Equations (9.3) and (9.4) can be written in the form of power functions to predict the discomfort caused by noise without vibration, and the discomfort caused by vibration without noise:

$$\psi_s = 0.119 \cdot 10^{0.035L_{AE}} \quad (9.12)$$

and

$$\psi_v = 70.8 (a_{VDV})^{0.947} \quad (9.13)$$

The discomfort caused by combined noise and vibration, ψ_c , can then be found by substituting ψ_s and ψ_v from Equations (9.12) and (9.13) in Equation (9.7):

$$\psi_c = [(0.119 \cdot 10^{0.035L_{AE}})^2 + (70.8 (a_{VDV})^{0.947})^2]^{0.5}, \quad (9.14)$$

for L_{AE} in the range 70 to 88 dBA, and a_{VDV} in the range 0.146 to 2.318 $\text{ms}^{-1.75}$. The correlation coefficient between the measured and the predicted values from Equation (9.14) (based on the physical magnitudes of stimuli) was 0.98 ($p < 0.01$; Spearman), slightly less than that between the measured and the predicted values from Equation (9.7) (based on the subjective magnitudes of stimuli).

9.5 Conclusion

Judgements of the discomfort caused by whole-body vibration can be reduced by the presence of noise, with the ‘masking effect’ increasing with increasing noise level. No statistically significant influence of vibration on judgements of noise discomfort were found, possibly due to the levels of noise and the magnitudes of vibration employed in the study.

The discomfort caused by combined noise and vibration was well predicted from the discomfort caused by noise in the presence of vibration, ψ'_s , and the discomfort caused by vibration in the presence of noise, ψ'_v , using multiple linear regression (i.e., $\psi_c = 18.46 + 0.47 \psi'_s + 0.20 \psi'_v$). Alternatively, the noise discomfort, ψ_s , and the vibration discomfort, ψ_v , can be combined in a root-sums-of-squares psychophysical model to predict the discomfort of combined noise and vibration, ψ_c (i.e., $\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}$). This root-sums-of-squares model is simpler, provided a better prediction, and is more convenient because standardised evaluations of noise and vibration can be used to estimate the discomfort caused by combined noise and vibration. For low-frequency random noise in the range 70 to 88 dBA and low-frequency random vertical whole-body vibration in the range 0.146 to 2.318 ms^{-1.75}, as used in the current study, the discomfort caused by combined noise and vibration was well predicted by: $\psi_c = [(0.119 \cdot 10^{0.035L_{AE}})^2 + (70.8 (a_{VDV})^{0.947})^2]^{0.5}$ where L_{AE} is the sound exposure level according to ISO 1996-1 (2003), and a_{VDV} is the vibration dose value according to BS 6841 (1987) or ISO 2631-1 (1997).

Chapter 10 Discussion

10.1 Introduction

This chapter brings together the findings of the different experiments during the whole study to address the three main objectives of the research: (i) to determine the relative importance of noise and vibration to the comfort experienced in cars, (ii) to understand the way in which the subjective responses to noise and vibration are influenced by each other, and (iii) to predict the total discomfort of simultaneous noise and vibration.

10.2 The subjective equivalence of noise and vibration

The subjective equivalence equation indicates the relative importance of noise and vibration to comfort, and therefore shows the situations in which either noise or vibration will dominate adverse subjective reactions.

In Chapter 5, the discomfort caused by noise was judged relative to that caused by vibration, and the equality of discomfort between simultaneous noise and vibration was obtained as:

$$L_{AE} = 80.4 + 14.7 \log_{10}(a_{VDV}). \quad (10.1)$$

In Chapter 6, when the discomfort caused by noise was judged relative to that caused by simultaneous vibration, the subjective equivalence equation was obtained as:

$$L_{AE} = 82.1 + 13.0 \log_{10}(a_{VDV}), \quad (10.2)$$

whereas when the discomfort caused by vibration was judged relative to that caused by simultaneous noise, the subjective equivalence equation was obtained as:

$$L_{AE} = 84.8 + 30.4 \log_{10}(a_{VDV}). \quad (10.3)$$

In chapter 7, various equations were obtained for various durations of stimuli. The subjective equality of discomfort between 4-s simultaneous noise and vibration were

$$L_{AE} = 83.2 + 13.6 \log_{10}(a_{VDV}), \quad (10.4)$$

when judging noise discomfort relative to vibration discomfort, and

$$L_{AE} = 85.4 + 21.1 \log_{10}(a_{VDV}), \quad (10.5)$$

when judging vibration discomfort relative to noise discomfort.

Contours showing the noise and vibration that produced equivalent discomfort in Chapters 5, 6 and 7 can be compared in Figure 10.1, with contours 1, 2, and 4 obtained from judging noise discomfort relative to vibration discomfort and contours 3 and 5 obtained from judging vibration discomfort relative to noise discomfort. These equivalence comfort contours for 4-s simultaneous noise and vibration are illustrated for the ranges of VDV's employed in each of the experiments.

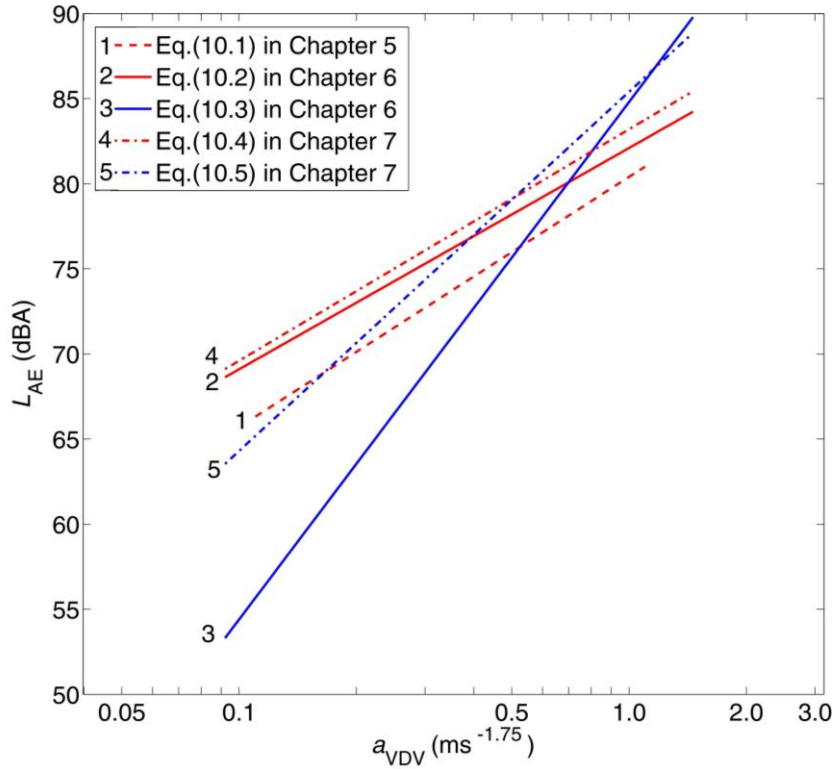


Figure 10.1 Comparison of equivalence contours between 4-s simultaneous noise and vibration (lines 1, 2 and 4: noise relative to vibration; lines 3 and 5: vibration relative to noise) from Chapters 5, 6, and 7.

When the discomfort caused by noise was the principal dependent variable (i.e., noise was judged relative to a reference vibration), similar slopes (i.e., 14.7, 13.0, and 13.6) for the equivalent comfort contours (i.e., Equations (10.1), (10.2), and (10.4)) were obtained. The equivalent comfort contours of Chapters 6 and 7 (i.e., Equations (10.2) and (10.4)) were similar, although using stimuli with no obvious meaning in Chapter 7 (random low-frequency noise and vibration) there was a slightly greater intercept (see Equation (10.4)) than in Chapter 6 (see Equation (10.2)) when using simulated stimuli (the synchronous car noise and vibration in cars). Suzuki *et al.*, (2006) found the discomfort caused by ‘irrelevant’ noises on running trains (e.g., receiving phone calls and white noise) was evaluated as being greater than the discomfort from simulated noise of running trains. In both that study and the present study, the differences in the discomfort caused by random noise (low frequency noise and white noise, often used in experiments concerned with noise perception) and the simulated noise (noise of running cars and trains) are negligible (less than 1 dB).

The different ranges of noise and vibration stimuli may influence the judgement of the relative discomfort of noise and vibration. The lower intercept in Equation (10.1) than in Equations (10.2) and (10.4) might be due to the wider range of SELs (61 to 91 dBA) and smaller range of VDV_s (0.11 to 1.10 ms^{-1.75}) employed in Chapter 5 than employed in Chapter 6 (70 to 88 dBA SEL and 0.092 to 1.458 ms^{-1.75} VDV) and Chapter 7 (70 to 88 dBA SEL and 0.092 to 1.431 ms^{-1.75} VDV).

The experiments in Chapters 5 and 6 employed simulated stimuli (the synchronous car noise and vibration in cars) with the same frequency spectra but different magnitudes. With VDV_s varying from 0.11 to 1.10 ms^{-1.75}, the range of predicted SELs varies from 66.3 to 81.0 dBA using Equation (10.1), and is much smaller than the range of noise stimuli (61 to 91 dBA) employed in Chapter 5; whereas with VDV_s varying from 0.092 to 1.458 ms^{-1.75}, the range of predicted SELs varies from 68.6 to 84.2 dBA using Equation (10.2), and is close to the range of noise stimuli (70 to 88 dBA) employed in Chapter 6. It seems in Chapter 5 the range of noise stimuli employed was too wide relative to the range of vibration stimuli, and the results are more likely to be biased than those in Chapter 6 in which a smaller range of noise stimuli and wider range of vibration stimuli were employed. Therefore Equation (10.1) is not preferred.

The experiments in Chapters 6 and 7 employed stimuli with the same magnitudes, but different characteristics (i.e., simulated stimuli in Chapter 6 and random stimuli in Chapter 7). With VDV_s varying from 0.092 to 1.458 ms^{-1.75}, the range of predicted SELs varied from 68.6 to 84.2 dBA using Equation (10.2) in Chapter 6, and varied from 69.1 to 85.4 dBA using Equation (10.4) in Chapter 7. There is no great difference between the two equivalence comfort contours, and the average value of the two intercepts, 82.7 dB, and the average slope, 13.3, may be used to approximate Equations (10.2) and (10.4) to within 0.4 dB. A similar slope of 14.4 with a much smaller intercept of 51.9 dB was found by Paulsen and Kastka (1995), who employed lower levels of simulated noise (from 28 to 61 dBA SPL) and similar magnitudes of simulated vibration (from 0.05 to 0.32 mm/s r.m.s. velocity). Possibly, the different intercepts may be attributed to the different ranges of stimuli investigated, whereas the slopes are not affected by the ranges of the stimuli.

When the discomfort caused by vibration was the principal dependent variable (i.e., vibration was judged relative to a reference noise), there were similar intercepts (i.e., 84.8 and 85.4 dB), but different slopes (i.e., 30.4 and 21.1) for the equivalence between noise and vibration (i.e., Equations (10.3) and (10.5)). The equivalence differed much for low magnitudes of noise and vibration, as shown in Figure 10.1. With VDV_s varying from 0.092 to 1.458 ms^{-1.75}, the range of predicted SELs varied from 53.3 to 89.8 dB using Equation (10.3), and the range of predicted SELs varied from 63.5 to 88.9 dB using Equation (10.5). The same magnitudes, but different characteristics of stimuli were employed in the two experiments, so it seems the discomfort caused by whole-body vibration is influenced by the meaning of the vibration stimulus, which is determined by their physical characteristics (e.g., the magnitude, frequency, direction). Further systematic studies are needed to understand the influence of the 'meaning of vibration' on subjective responses to whole-body vibration. Nevertheless, here the average value of the intercepts in Equations (10.3) and (10.5), 84.3 dB, and the average slope, 25.8, are proposed tentatively as a compromise for simulated and random stimuli.

From Figure 10.1, if noise is the principal dependent variable, lines 2 and 4 may be appropriate, where the average intercept, 82.7 dB, and the average slope, 13.3 of Equations (10.2) and (10.4) are proposed for applications. If vibration is the principal dependent variable, lines 3 and

5 may be appropriate, where the average intercept, 84.3 dB, and the average slope, 25.8 of Equations (10.3) and (10.5) are proposed for applications. The average slope of Equations (10.2) to (10.5) is around 20, which is similar to the assumed value of 21 in the previous studies (Chapters 5 and 6). Therefore the average values of 20 and 83.5 dB as the slope and intercept of the equivalence comfort contour may seem a sensible compromise for practical applications over a range of SELs from 61 to 91 dBA and VDV_s from 0.092 to 1.458 ms^{-1.75}. The investigation of the effect of the ranges and the meaning of noise and vibration on discomfort judgements is suggested for future study.

10.3 The influence of noise and vibration to each other in the subjective judgements

It was found in Chapters 5, 6, and 7 that higher magnitude vibrations tend to 'mask' (i.e., reduce) the discomfort caused by low levels of noise, and that higher levels of noise tend to 'mask' the discomfort caused by low magnitudes of vibration. The masking effects of 'vibration on noise' and 'noise on vibration' were greater when employing RME with cross-modality judgements (i.e., judging noise discomfort relative to vibration discomfort, or judging vibration discomfort relative to noise discomfort) employed in Chapters 5, 6 and 7. When using AME in Chapter 9, there were no significant effects of simultaneous vibration on the judgement of noise discomfort, and smaller masking effects of noise on the judgement of vibration discomfort than in the previous experiments using RME.

Noise tended to reduce judgements of vibration discomfort in Chapter 9, consistent with the masking effects of noise on vibration found in Chapters 5, 6, and 7, and also consistent with Miwa and Yonekawa (1973) and partly consistent with Howarth and Griffin (1990a) who found that annoyance caused by low magnitudes of vibration was reduced by high levels of noise. A synergistic effect of noise on judgements of vibration discomfort was also suggested in previous studies: Kirby *et al.*, (1977) found the discomfort caused by vibration (0.5, 1.0 and 1.5 ms⁻² peak) was greater when presented with noise at 85 dBA than when presented with noise at 60 dBA, and Howarth and Griffin (1990a) investigated low magnitudes of vibration (0.02 to 0.125 ms⁻² r.m.s.) and low levels of noise (40 to 65 dBA SPL) and found a synergistic effect of noise on vibration annoyance with 'relatively high' magnitudes of vibration. However, the conclusion of a synergistic effect of noise in the two studies is questionable: Kirby *et al.*, (1977) asked subjects to rate the discomfort caused by different combinations of noise and vibration, not the vibration discomfort, so their conclusion on a synergistic effect might not be the 'effect of noise on vibration'; the tendency of a synergistic effect was not obvious enough in the study of Howarth and Griffin (1990a, Figure 6). In the present study, the synergistic effect of noise on the judgement of vibration discomfort was not observed by investigating the SELs from 70 to 88 dBA and the VDV_s from 0.146 to 2.318 ms^{-1.75}.

Whether noise or vibration is the dominant influence on subjective judgements of noise and vibration when they are presented simultaneously depends on their relative magnitudes. The

findings in Chapters 6 and 7 with SELs from 70 to 88 dBA and VDV_s from 0.092 to 1.458 ms^{-1.75} indicated that judgements of vibration discomfort were more likely to be influenced by noise than judgements of noise discomfort were influenced by vibration. The findings in Chapter 9 with SELs from 70 to 88 dBA and VDV_s from 0.146 to 2.318 ms^{-1.75} indicated there was no significant influence of vibration on judgements of noise discomfort, consistent with previous studies (e.g., Dempsey *et al.* (1976) with SPLs from 70 to 85 dBA and r.m.s. accelerations from 0.3 to 1.2 ms⁻²; Howarth and Griffin (1990a) with SPLs from 40 to 65 dBA and r.m.s. accelerations from 0.02 to 0.125 ms⁻²; Seidel *et al.* (1990) with SPLs from 65 to 85 dBA and r.m.s. accelerations from 0.55 to 2.2 ms⁻²). Paulsen and Kastka (1995) and Parizet *et al.* (2004) suggested there was an influence of vibration on judgements of noise, because they employed low noise levels (between 32 and 60 dBA SPL) and relatively high vibration magnitudes (between 0.1 to 0.8 ms⁻² r.m.s.).

The influence of noise on subjective judgements of vibration and the influence of vibration on subjective judgement of noise might depend on the durations of the stimuli. The discomfort caused by noise and vibration over durations from 2 to 32 s was investigated in Chapter 7. The results showed that the influence of noise on the judgement of vibration discomfort decreases as the durations of the stimuli increase, whereas the influence of the noise on the judgements of vibration is independent of the duration.

10.4 The total discomfort of simultaneous noise and vibration

In Chapter 9, a root-sums-of-squares (r.s.s.) model was proposed to determine the discomfort caused by simultaneous noise and vibration from the discomfort caused by noise and the discomfort caused by vibration:

$$\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}, \quad (10.6)$$

where ψ_c , ψ_s , and ψ_v represent the discomfort caused by combined noise and vibration, noise alone, and vibration alone, respectively. The r.s.s. model is a more convenient model and gives a more accurate prediction of the total discomfort of noise and vibration than the multiple regression equation in Chapter 9 (i.e., Equation (9.6)).

The r.s.s. model (i.e., Equation (10.6)) could be used to predict the discomfort caused by combined noise and vibration from the physical magnitudes of the stimuli, by using the psychophysical relationships between the subjective magnitudes of noise and vibration and their physical magnitudes in the present study (i.e., Equations (9.12) and (9.13)):

$$\psi_c = [(0.119 \cdot 10^{0.035L_{AE}})^2 + (70.8 (a_{VDV})^{0.947})^2]^{0.5}, \quad (10.7)$$

for L_{AE} in the range 70 to 88 dBA, and a_{VDV} in the range 0.146 to 2.318 ms^{-1.75}.

The r.s.s. model is also compatible with the psychophysical equations suggested in other studies (e.g., Howarth and Griffin, 1990a, 1991). Howarth and Griffin (1990a) found the following equations to predict the discomfort caused by noise and the discomfort caused by vibration:

$$\psi_s = 0.217 \cdot 10^{0.039L_{AE}}, \quad (10.8)$$

and

$$\psi_v = 245 (a_{VDV})^{1.04}, \quad (10.9)$$

Substituting Equations (10.8) and (10.9) into Equation (10.6), the total annoyance could be predicted by:

$$\psi_c = [(0.217 \cdot 10^{0.039L_{AE}})^2 + (245 (a_{VDV})^{1.04})^2]^{0.5} \quad (10.10)$$

for L_{AE} in the range 54 to 79 dBA and a_{VDV} in the range 0.07 to 0.40 $\text{ms}^{-1.75}$. The values predicted by this equation are highly correlated with the values predicted by the multiple regression equation (i.e., Equation (2.38)) proposed by Howarth and Griffin (1990a) (0.98; $p < 0.01$, Spearman).

Using Equation (10.6) to predict the further findings of Howarth and Griffin (1991), the total annoyance caused by simultaneous noise and vibration would be predicted by:

$$\psi_c = [(0.307 \cdot 10^{0.036L_{AE}})^2 + (371 (a_{VDV})^{1.18})^2]^{0.5}, \quad (10.11)$$

for L_{AE} in the range 52.5 to 75.8 dBA and a_{VDV} in the range 0.056 to 0.40 $\text{ms}^{-1.75}$. The predicted values are also highly correlated with the values predicted by the multiple regression equation (i.e., Equation (2.40)) proposed by Howarth and Griffin (1991) (0.99; $p < 0.01$, Spearman).

In the 1990 and 1991 studies of Howarth and Griffin, the subjective magnitudes of noise alone and vibration alone were used in the multiple regression, but neither of the two multiple regression equations (i.e., Equation (2.38) and Equation (2.40)) is applicable in the absence of noise or vibration (i.e., when $\psi_s = 0$ or $\psi_v = 0$) because the multiple regression equations are limited by the errors of regression. Compared with the multiple regression equations, the root-sum-of-squares (r.s.s.) equation (i.e., Equation (10.6)) is applicable in the absence of noise or vibration (e.g., when there is no noise, Equation (10.6) becomes to $\psi_c = \psi_v$).

The r.s.s. model implies an interaction between noise and vibration in the subjective judgements, as indicated in Chapter 9: the relative contribution to the total discomfort caused by either stimulus (noise or vibration) reduces as the magnitude of the other stimulus (vibration or noise) increases. The 'masking effect' in the r.s.s. model is symmetrical, whereas in Chapters 6, 7 and 9 it was observed that noise was more likely to 'mask' the vibration discomfort than vibration would 'mask' the noise discomfort. However, noise discomfort may be masked by vibration if either lower levels of noise or greater magnitudes of vibration are employed. Although Equation (10.6) was obtained from subjective judgements of random low-frequency noise and vertical whole-body vibration, it might be applicable to predicting the total discomfort with other types of noise (e.g., different frequency spectra) and other types of vibration (e.g., different frequency spectra, different directions, and different locations of application of vibration to the body). More speculatively, the total discomfort caused by different environmental stresses or modalities (e.g., noise, vibration, temperature, etc.) might be predicted by the r.s.s. of the discomfort caused by each stressor:

$$\psi_c = [(\psi_1)^2 + (\psi_2)^2 + \dots + (\psi_n)^2]^{0.5}, \quad (10.12)$$

where ψ_c represents the total discomfort caused by all stressors and $\psi_1, \psi_2, \dots, \psi_n$ represent the discomfort caused by each stressor. Vibration discomfort is already predicted by assuming this approach (e.g., the overall discomfort of multiple axis vibration is usually determined by the r.s.s. of the equivalent discomfort caused by each axis of vibration (British Standard Institute, 1987)).

Although the r.s.s. method is convenient, the fourth power summation method is sometimes used (e.g., the VDV or root-mean-quad (British Standard Institute, 1987; International Organization for Standardization, 1997). In the present study, if the fourth power, (i.e., root-sum-of-quad, r.s.q.), is used instead of the second power (i.e., r.s.s.) as in Equation (10.6):

$$\psi_c = [(\psi_v)^4 + (\psi_s)^4]^{0.25}. \quad (10.13)$$

The correlation between the measured and predicted values from Equation (10.13) is 0.98 ($p < 0.001$; Spearman), slightly less than the correlation coefficient between the measured and predicted values from Equation (10.6). More intuitive, the Euclidean distance² between the measured and predicted values from Equation (10.13) is 94.5, somewhat greater than the 58.3 between the measured and predicted values from Equation (10.6). On the basis of the current results, the r.s.s. approach therefore seems more appropriate than the r.s.q. approach.

10.5 Application of results

The equivalence curves and equations indicated in Section 10.2 are directly applicable to the design of noise and vibration in vehicles: from small cars (e.g., the Global Electric Motorcars) to heavy trucks. The r.s.s. model proposed in Section 10.4 might be applicable to predicting the combined discomfort caused by noise and vibration in the working, living and the driving environment.

² Euclidean distance: In general, if $\mathbf{p} = (p_1, p_2, \dots, p_n)$ and $\mathbf{q} = (q_1, q_2, \dots, q_n)$ for an n-dimensional

space, the distance from $\mathbf{p}$ to $\mathbf{q}$ is given by: $d(\mathbf{p}, \mathbf{q}) = \sqrt{\sum_{i=1}^n (q_i - p_i)^2}$.

Chapter 11 Conclusions and recommendations

11.1 Conclusions

The vibration and noise related to gear-shifts are judged differently by drivers judging 'responsiveness' and passengers judging 'discomfort'. For drivers, judgements of responsiveness are greatest with minimum delay in changes of synchronous noise and vibration after a gear-shift, and reduce with increasing delay. Judgements of responsiveness are more influenced by a delay in vibration than that a delay in noise when vibration and noise are delayed independently. For passengers, judgements of discomfort are independent of delays between the vibration and noise associated with gear-shifts, but increase with increasing sound level. The experimental results suggest further research on passenger comfort with combined noise and vibration is needed to understand the judgement of combined noise and vibration.

The relative discomfort caused by noise and vibration can be predicted from a subjective equivalence equation. In the laboratory studies reported in this thesis, the equivalence between noise and vibration was highly dependent on whether the subjects were asked to rate the discomfort caused by noise, or the discomfort caused by vibration. The equivalence equation may be approximated by $L_{AE} = 82.7 + 13.3 \log_{10}(a_{VDV})$ if noise is the principal dependent variable (i.e., subjects judge noise relative to vibration), but may be approximated by $L_{AE} = 84.3 + 25.8 \log_{10}(a_{VDV})$ if vibration is the principal dependent variable (i.e., vibration is judged relative to noise). Over durations of stimuli from 2 to 32 s, the slopes in these equivalence equations increased with increasing duration when judging noise relative to vibration, but were independent of duration when judging vibration relative to noise.

There was a 'masking effect' of noise on judgements of vibration discomfort, and a 'masking effect' of vibration on judgements of noise discomfort. The masking effects depended on the relative magnitudes of the noise and the vibration. With SEL in the range 70 to 88 dBA and VDV in the range 0.15 to 2.32 $\text{ms}^{-1.75}$, the discomfort caused by vibration was reduced by the presence of noise, while the discomfort caused by noise was not influenced by the presence of vibration discomfort.

The combined discomfort caused by simultaneous noise and vibration was greater than the discomfort caused by noise alone and greater than the discomfort caused by vibration alone, but was not simply the summation of the noise discomfort and the vibration discomfort. The combined discomfort caused by simultaneous noise and vibration can be predicted by a root-sums-of-squares (r.s.s.) of the discomfort caused by noise and the discomfort caused by vibration when they were presented separately (i.e., $\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}$, where ψ_v , ψ_s , and ψ_c , represent vibration discomfort, noise discomfort, and their total discomfort, respectively). For low-frequency noise from 70 to 88 dBA SEL and the low-frequency whole-body vertical vibration from 0.15 to 2.32 $\text{ms}^{-1.75}$ VDV, the equation $\psi_c = \{[0.119(\phi_s)^{0.035}]^2 + [70.8(\phi_v)^{0.947}]^2\}^{0.5}$, provides

useful predictions of the discomfort caused by combined noise and vibration, where $\varphi_v = a_{VDV}$ ($\text{ms}^{-1.75}$) and $\log_{10}(\varphi_s) = L_{AE}$ (dBA).

11.2 Recommendations

11.2.1 Procedure for evaluating combined noise and vibration

It is recommended that the following procedure is adopted to predict the total discomfort caused by combined noise and vibration:

- 1) The magnitude of vibration is determined by the VDV, a_{VDV} , as:

$$a_{VDV} = \left(\int_0^T a^4(t) dt \right)^{1/4}, \quad (11.1)$$

where $a(t)$ is the frequency-weighted acceleration and T is the duration of the measurement period in seconds (British Standards Institution, 1987; International Organization for Standardization, 1997).

- 2) The magnitude of noise can be determined by the A-weighted SEL, L_{AE} , as:

$$L_{AE} \text{ (dBA)} = 10 \log_{10} \left(\frac{1}{t_0} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right), \quad (11.2)$$

where $p_A(t)$ is the instantaneous A-weighted sound pressure starting at time t_1 and ending at time t_2 , p_0 is the reference sound pressure, 20 μPa , and t_0 is the reference duration of 1 s (International Organization for Standardization, 2003a).

The combined use of the VDV and the SEL may not be appropriate for stimuli having durations longer than a few minutes.

- 3) The subjective equivalence equation can be applied to determine whether the discomfort caused by noise or the discomfort caused by vibration is dominant in the environment:

$$L_{AE} = 82.7 + 13.3 \log_{10}(a_{VDV}), \quad (11.3)$$

if noise is judged relative to vibration, and

$$L_{AE} = 84.3 + 25.8 \log_{10}(a_{VDV}), \quad (11.4)$$

if vibration is judged relative to noise.

- 4) The total discomfort caused by simultaneous noise and vibration, ψ_c , can be estimated from:

$$\psi_c = [(\psi_v)^2 + (\psi_s)^2]^{0.5}, \quad (11.5)$$

where ψ_v represents the discomfort caused by vibration in the absence of noise and ψ_s is the discomfort caused by noise in the absence of vibration.

The values of ψ_v and ψ_s (i.e., the subjective magnitudes of vibration and noise), can be determined in a subjective experiment or they may be predicted by the following equations:

$$\psi_s = 0.119(\varphi_s)^{0.035}, \quad (11.6)$$

$$\psi_v = 70.8(\varphi_v)^{0.947}, \quad (11.7)$$

where $\varphi_v = a_{VDV}$ ($\text{ms}^{-1.75}$), and $\log_{10}(\varphi_s) = L_{AE}$ (dBA), for the low-frequency noise from 70 to 88 dBA and the low-frequency vertical whole-body vibration from 0.15 to 2.32 $\text{ms}^{-1.75}$.

The numerical value of total discomfort, ψ_c , obtained from Equation (11.5) can be employed to compare the discomfort caused by different combinations of vibration and noise.

11.2.2 Future research

Currently, a 3-dB reduction of the sound level is assumed to be required to maintain the same discomfort associated with noise when there is a doubling of noise duration (International Organization for Standardization, 2003a), whereas a 1.5-dB reduction of the vibration magnitude is needed to maintain the same discomfort associated with vibration when there is a doubling of vibration duration (British Standards Institution, 1987; International Organization for Standardization, 1997). The findings in Chapter 7 suggest the rate of increase in discomfort with increasing duration should be similar for noise and vibration, so either SEL has an inappropriate duration-dependence for noise discomfort or VDV has an inappropriate duration-dependence for vibration discomfort, or both are inappropriate. Further investigations are required to determine the appropriate duration-dependence for noise discomfort and vibration discomfort.

When using relative magnitude estimation with the cross-modality procedure, (i.e., judging the discomfort caused by noise relative to a reference vibration, and judging the discomfort caused by vibration relative to a reference noise (Chapters 5, 6 and 7), the equivalence in comfort between noise and vibration was largely dependent on whether the noise was judged relative to vibration, or the vibration was judged relative to noise. It might be expected after long exposures to simultaneous noise and vibration, the effect of the principal variable (i.e., whether the noise was judged relative to vibration, or the vibration was judged relative to noise) will vanish, and the subjective equivalence between noise and vibration will be the same no matter whether noise is judged relative to vibration or vibration is judged relative to noise (Chapter 7). Therefore, further studies of the relative discomfort of noise and vibration are needed with long duration stimuli.

With the stimuli investigated here, the total discomfort caused by simultaneous noise and whole-body vertical vibration is well approximated by the r.s.s. of the discomfort caused by the noise alone and the discomfort caused by the vibration alone. This was applicable in the present study (Chapter 9) and in the Howarth and Griffin studies (1990a, 1991). Whether it is applicable with other noise and vibration environments merits further investigations. A universal model for the total discomfort caused by different environmental stresses was hypothesized as $\psi_c = [(\psi_1)^2$

$+ (\psi_2)^2 + \dots + (\psi_n)^2]^{0.5}$, where $\psi_1, \psi_2, \dots, \psi_n$ represent the discomfort caused by each stressor when presented alone. Research to confirm or disprove this model merits further study.

The contribution of vision to judgements of the discomfort caused by noise and vibration might be considered for future laboratory experiments investigating subjective responses to noise and vibration in cars, trains, aircraft, buildings, etc. The discomfort caused by noise and vibration might either be reduced by the vision because of the 'informational masking' of vision on the subjective experience (Watson, 2005), or increased by the vision because the subjective experience might be enhanced by the visibility of the real environment (e.g., the sight inside a vehicle and outside the window).

Appendix A Instructions to Subjects

A.1 Instructions to Subjects in the First Experiment Reported in Chapter 4

Instructions to passenger

You will be presented with a series of combined motions and sounds. This experiment is to determine your impression of ride quality caused by driver commands (i.e. gear shift) and consequent changes in motion and sound.

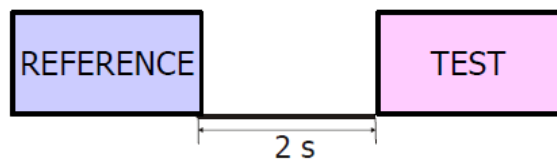
Please read carefully and follow the instructions below.

--- Preparation ---

- Sit comfortably in the seat, resting your feet on the footrest. Please maintain your body posture: (i) **sitting upright**, (ii) **back on the backrest**, during the test.
- Please find an **emergency stop button** placed beside you. You will be asked to wear a pair of headphones and a blindfold.
- 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 any question if unsure.

--- Procedure ---

- You will be presented with a reference stimulus followed by a test stimulus. The reference stimulus consists of a fixed combination of motion and sound, which represents an **overall DISCOMFORT of 100**.



- Your task is to estimate the **DISCOMFORT** of the test stimulus using any numbers, such as 10, 30, 100, 150, 200...
- If the **DISCOMFORT** of the TEST is **twice** as the REFERENCE, say **200**. If the **DISCOMFORT** of the TEST is **half** as the REFERENCE, say **50**.
- Please always remember you are sitting inside a car and the driver is changing the gear, and remember that you are evaluating the **combined** noise and vibration, **not only** vibration or noise.
- Say **“Repeat”** if unsure.

Instruction to driver

You will be presented with a series of combined motions and sounds. This experiment is to determine your impression of ride quality caused by your commands (i.e. gear shift) and consequent changes in motion and sound.

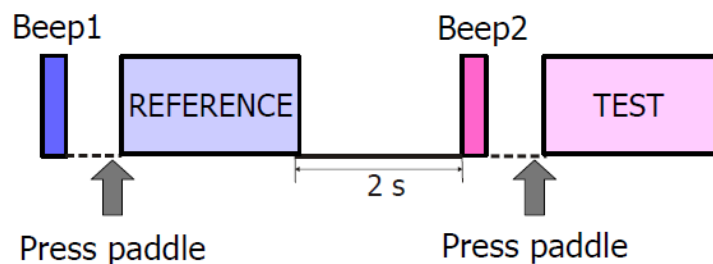
Please read carefully and follow the instructions below.

--- Preparation ---

- Sit comfortably in the seat, resting your feet on the footrest and holding the steering wheel. Please maintain your body posture: (i) sitting upright, (ii) back on the backrest, during the test.
- Please find gear paddles at the back of the steering wheel. Press the Left paddle will active motion and sound stimuli.
- Please find an **emergency stop button** placed beside you. You will be asked to wear a pair of headphones and a blindfold.
- 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 any question if unsure.

--- Procedure ---

- You will be presented with a reference stimulus followed by a test stimulus. The reference stimulus consists of a fixed combination of motion and sound, which represents an overall RESPONSIVENESS of 100.
- Each stimulus will be activated by you pressing the Left gear paddle. Please active the paddle about 1 s after you hear a 'beep' sound.



- Your task is to estimate the RESPONSIVENESS of the test stimulus using any numbers, such as 10, 30, 100, 150, 200...
- If the RESPONSIVENESS of the TEST is **twice** as good as the reference, say **200**. If the RESPONSIVENESS of the TEST is **half**, say **50**.
- Please always remember you are the driver changing the gear, and always remember that you are evaluating the **combined** noise and vibration, **not only** vibration or noise.
- Say **"Repeat"** if unsure.

A.2 Instructions to Subjects in the Second Experiment Reported in Chapter 5

Instructions

You will be presented with a series of simultaneous vibrations and sounds. This experiment is to determine your impression of discomfort in vehicles.

Please read carefully and follow the instructions below.

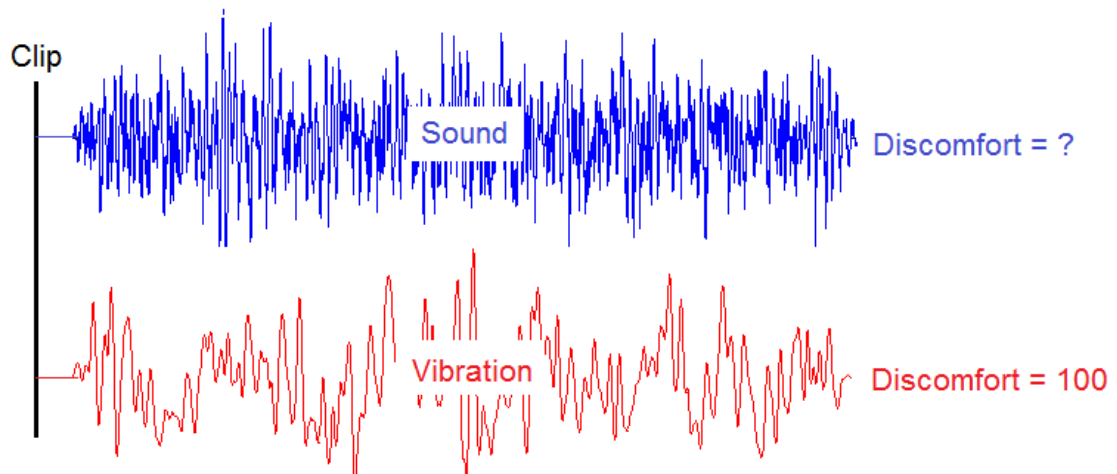
Session A

--- Preparation ---

- Sit comfortably in the seat, and maintain your body posture: **sitting upright** during the tests.
- You will be asked to wear a pair of headphones and a blindfold.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.
- 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.

--- Procedure ---

- You will be presented with series of simultaneous sound and vibration stimuli.
- Each stimulus will be preceded by a very low '**clip**' sound, which should be ignored.



- Your task is to say the **DISCOMFORT** of the **sound**, assuming the **DISCOMFORT** of the **vibration** is **100**.
- Please imagine you are sitting inside a car.
- Say "**Repeat**" if you are unsure.

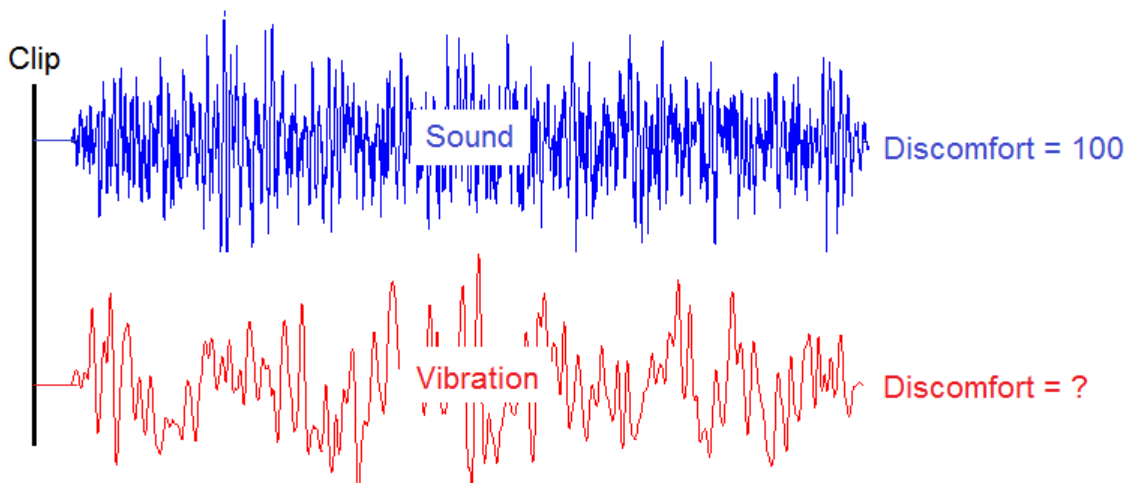
Session B

--- Preparation ---

- Sit comfortably in the seat, and maintain your body posture: **sitting upright** during the tests.
- You will be asked to wear a pair of headphones and a blindfold.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.
- 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.

--- Procedure ---

- You will be presented with series of simultaneous sound and vibration stimuli.
- Each stimulus will be preceded by a very low 'clip' sound, which should be ignored.



- Your task is to say the **DISCOMFORT** of the **vibration**, assuming the **DISCOMFORT** of the **sound** is **100**.
- Please imagine you are sitting inside a car.
- Say "**Repeat**" if you are unsure.

A.3 Instructions to Subjects in the Third Experiment Reported in Chapter 6

Instructions

You will be presented with a series of vibrations and sounds. This experiment is to determine your impression of discomfort in vehicles.

Please read carefully and follow the instructions below.

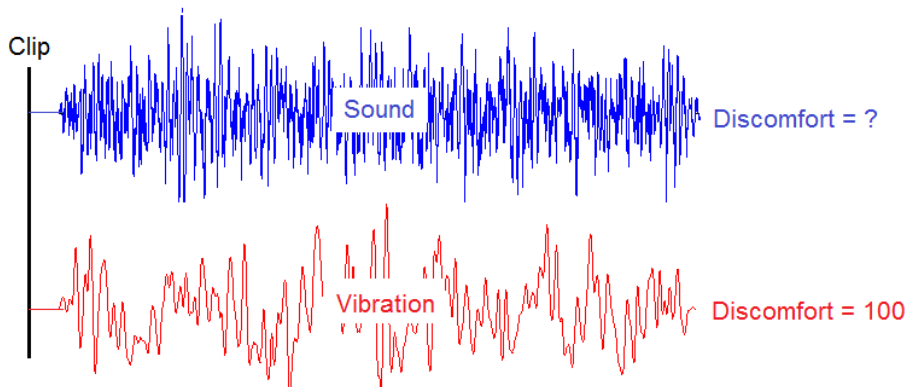
--- Preparation ---

- Sit comfortably in the seat, and maintain your body posture: **sitting upright** during the tests.
- You will be asked to wear a pair of headphones and close your eyes.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.
- 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.

Session A

--- Procedure ---

- You will be presented with series of **simultaneous** sound and vibration stimuli.
- Each stimulus will be preceded by a very low '**clip**' sound, which should be ignored.

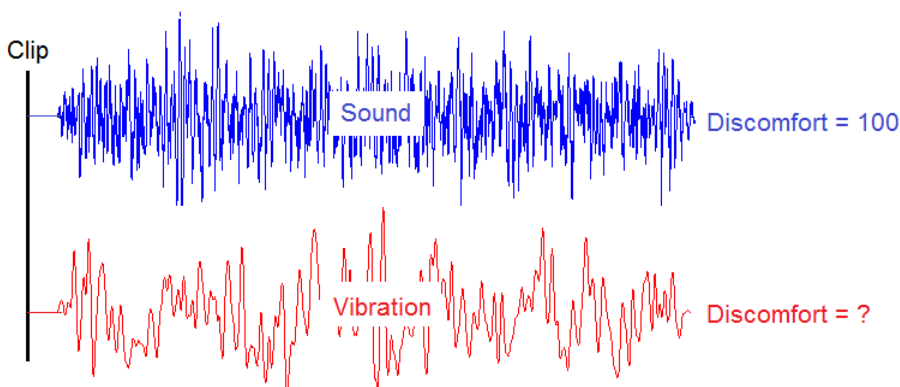


- Your task is to say the **DISCOMFORT** of the **sound**, assuming the **DISCOMFORT** of the **reference vibration** is **100**.
 - The **reference vibration** may **change** for each exposure, so please concentrate.
 - Say "**Repeat**" if you are unsure.
-

Session B

--- Procedure ---

- You will be presented with series of **simultaneous** sound and vibration stimuli.
- Each stimulus will be preceded by a very low '**clip**' sound, which should be ignored.

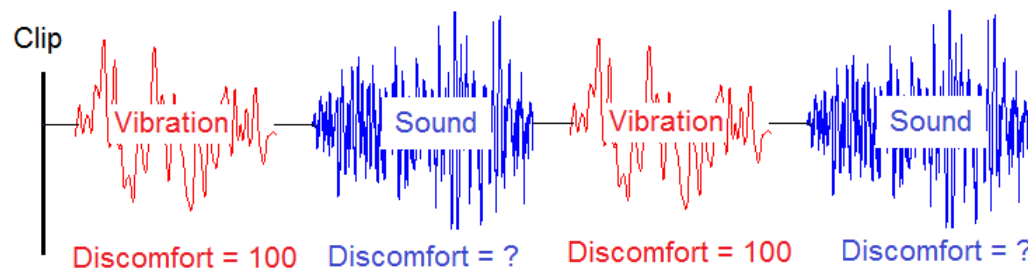


- Your task is to say the **DISCOMFORT** of the **vibration**, assuming the **DISCOMFORT** of the **sound** is **100**.
- The **reference sound** may **change** for each exposure, so please concentrate.
- Say "**Repeat**" if you are unsure.

Session C

--- Procedure ---

- You will be presented with series of **sequential** sound and vibration stimuli.
- Each stimulus will be preceded by a very low ‘**clip**’ sound, which should be ignored.

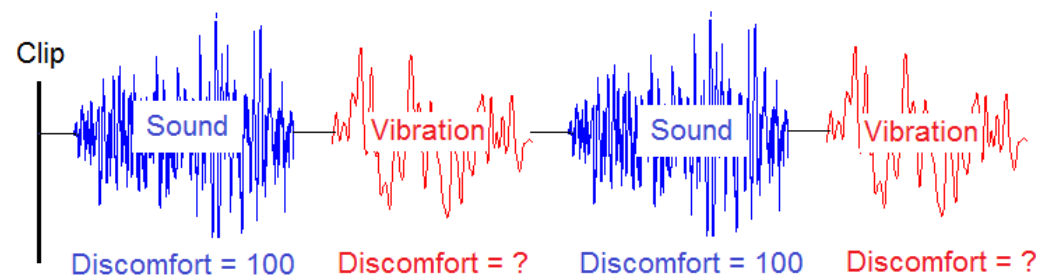


- Your task is to say the **DISCOMFORT** of the **sound**, assuming the **DISCOMFORT** of the **reference vibration** is **100**.
 - The **reference vibration** may **change** for each exposure, so please concentrate.
 - Say “**Repeat**” if you are unsure.
-

Session D

--- Procedure ---

- You will be presented with series of **sequential** sound and vibration stimuli.
- Each stimulus will be preceded by a very low ‘**clip**’ sound, which should be ignored.



- Your task is to say the **DISCOMFORT** of the **vibration**, assuming the **DISCOMFORT** of the **sound** is **100**.
- The **reference sound** may **change** for each exposure, so please concentrate.
- Say “**Repeat**” if you are unsure.

A.4 Instructions to Subjects in the Fourth Experiment Reported in Chapter 7

Instructions

This experiment is to determine your impression of discomfort in vehicles.

You will be presented with a series of vibrations and sounds.

Please read carefully and follow the instructions below.

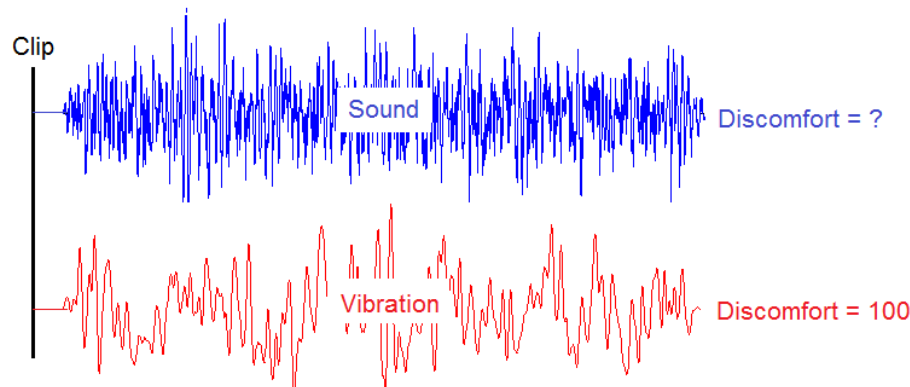
--- Preparation ---

- Sit comfortably in the seat, and maintain your body posture: **sitting upright** during the tests.
- Wear a pair of headphones and close your eyes.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.
- 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.

Session A

--- Procedure ---

- You will be presented with series of **simultaneous** sound and vibration stimuli.
- Each stimulus will be preceded by a very low '**clip**' sound, which should be ignored.

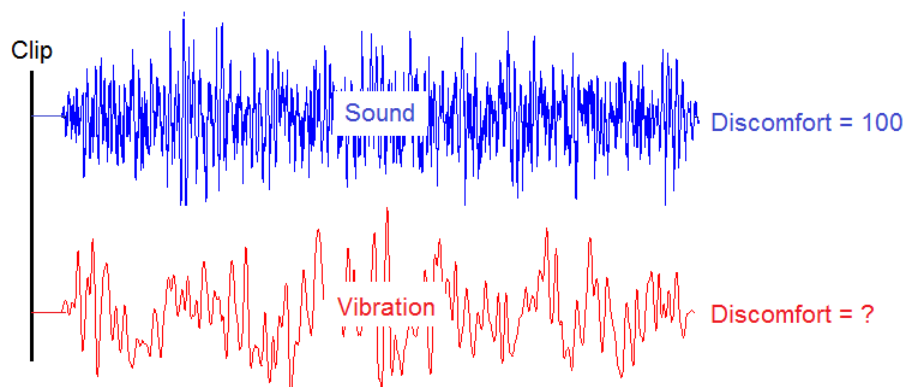


- Your task is to say the **DISCOMFORT** of the **sound**, assuming the **DISCOMFORT** of the **reference vibration** is **100**.
 - The **reference vibration** may **change** for each exposure, so please concentrate.
 - Say "**Repeat**" if you are unsure.
-

Session B

--- Procedure ---

- You will be presented with series of **simultaneous** sound and vibration stimuli.
- Each stimulus will be preceded by a very low '**clip**' sound, which should be ignored.



- Your task is to say the **DISCOMFORT** of the **vibration**, assuming the **DISCOMFORT** of the **sound** is **100**.
- The **reference sound** may **change** for each exposure, so please concentrate.
- Say "**Repeat**" if you are unsure.

A.5 Instructions to Subjects in the Fifth Experiment Reported in Chapter 8

Instructions

You will be presented with a series of vibrations and sounds. This experiment is to determine your impression of discomfort in vehicles.

Please read carefully and follow the instructions below.

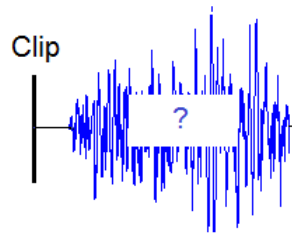
--- Preparation ---

- Sit comfortably in the seat, and maintain your body posture: **sitting upright** during the tests.
- You will be asked to wear a pair of headphones and close your eyes.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.
- 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.

Session A – part 1

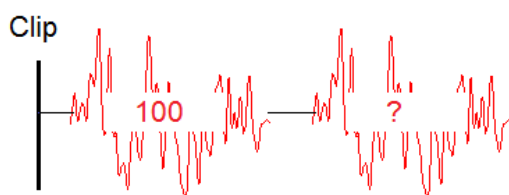
--- Procedure ---

- You will be presented with different levels of **sound** stimuli.
- Your task is to say the **DISCOMFORT** of the **sound** using **any numerical value**.
- Please imagine you are sitting inside a car.
- Say “**Repeat**” if you are unsure.

**Session A – part 2**

--- Procedure ---

- You will be presented with a **reference vibration** and different magnitudes of **test vibration**.
- Your task is to say the **DISCOMFORT** of the **test vibration**, assuming the **DISCOMFORT** of the **reference vibration** is **100**.
- Please imagine you are sitting inside a car.
- Say “**Repeat**” if you are unsure.



Session A – part 1

--- Procedure ---

- You will be presented with different levels of **vibration** stimuli.
- Your task is to say the **DISCOMFORT** of the **vibration** using **any numerical value**.
- Please imagine you are sitting inside a car.
- Say “**Repeat**” if you are unsure.

Clip

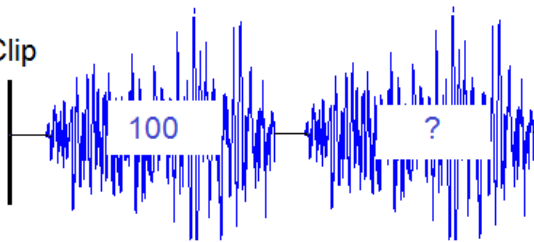


Session A – part 2

--- Procedure ---

- You will be presented with a **reference sound** and different magnitudes of **test sound**.
- Your task is to say the **DISCOMFORT** of the **test sound**, assuming the **DISCOMFORT** of the **reference sound** is **100**.
- Please imagine you are sitting inside a car.
- Say “**Repeat**” if you are unsure.

Clip



A.5 Instructions to Subjects in the Sixth Experiment Reported in Chapter 9

Instructions

This experiment is designed to understand your impression of discomfort in vehicles.

You will be presented with a series of vibration and sound stimuli.

Please read carefully and follow the instructions below.

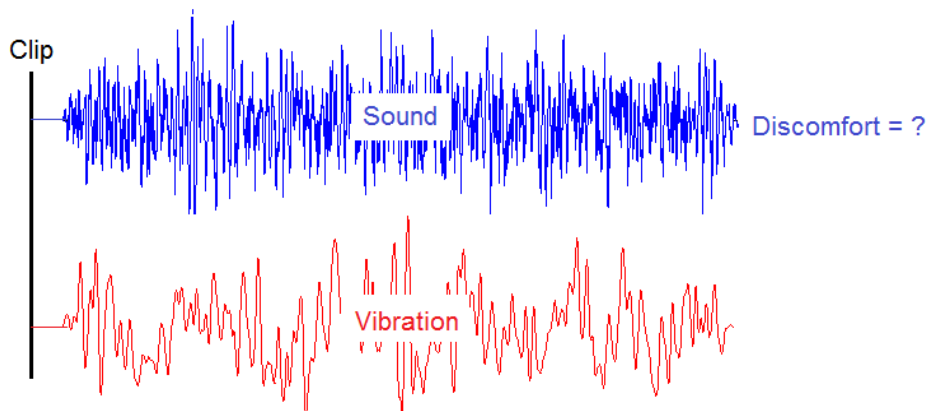
--- Preparation ---

- Sit comfortably in the seat, and maintain your body posture: **sitting upright** during the tests.
- You will be asked to wear a pair of headphones and close your eyes.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.
- 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.

Session A: Rate the discomfort of sound

--- Procedure ---

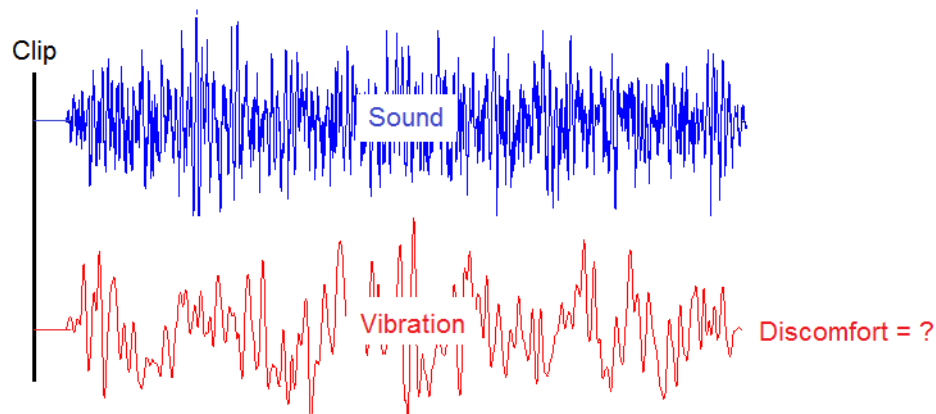
- You will be presented with series of **simultaneous** sound and vibration stimuli.
- Each stimulus will be preceded by a very low “clip” sound.
- Your task is to say the **DISCOMFORT** of the **sound** using **any positive number** that appears appropriate – **whole numbers, decimals or fractions**.
- Please imagine you are sitting inside a car.
- Say “**Repeat**” if you are unsure.



Session B: Rate the discomfort of vibration

--- Procedure ---

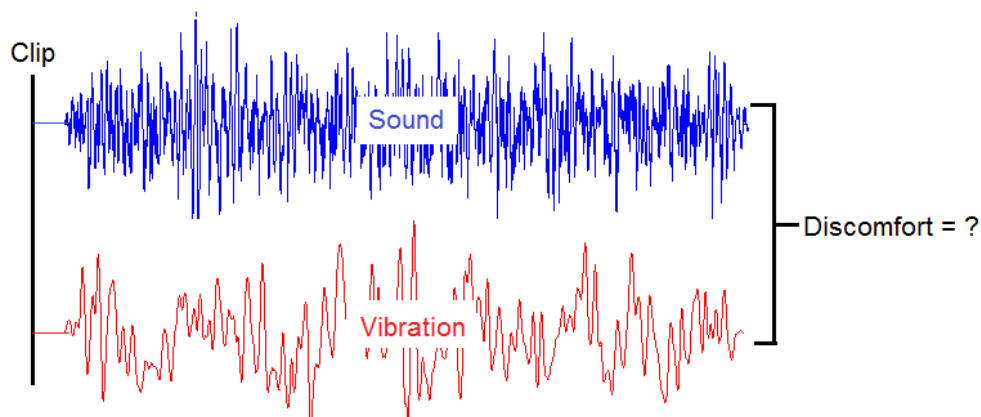
- You will be presented with series of **simultaneous** sound and vibration stimuli.
- Each stimulus will be preceded by a very low “clip” sound.
- Your task is to say the **DISCOMFORT** of the **vibration** using **any positive number** that appears appropriate – **whole numbers, decimals or fractions**.
- Please imagine you are sitting inside a car.
- Say “**Repeat**” if you are unsure.



Session C: Rate the discomfort of combined noise and vibration

--- Procedure ---

- You will be presented with series of **simultaneous** sound and vibration stimuli.
- Each stimulus will be preceded by a very low “clip” sound.
- Your task is to say the **DISCOMFORT** of the “**overall situation**” – the **combination of noise and vibration** using **any positive number** that appears appropriate – **whole numbers, decimals or fractions**.
- Please imagine you are sitting inside a car.
- Say “**Repeat**” if you are unsure.



Appendix B Individual Results of Experiment 5 in Chapter 8

Table B.1 The exponents (n_v and n_s), the constants (k_v and k_s), and Spearman's rank correlation coefficients (r_v and r_s), obtained with RME and AME methods of 20 subjects when judging the discomfort of vibration (ψ_v) and the discomfort of noise (ψ_s). First repetition.

1 st	ψ_v RME			ψ_v AME			ψ_s RME			ψ_s AME		
No.	n_{vr1}	k_{vr1}	r_{vr1}	n_{va1}	k_{va1}	r_{va1}	n_{sr1}	K_{sr1}	r_{sr1}	n_{sa1}	k_{sa1}	r_{sa1}
1	0.84	862.00	0.90	1.95	2129.30	0.96	1.39	0.00	0.97	1.39	0.00	0.91
2	0.27	168.89	0.92	0.69	250.35	0.87	0.63	0.44	0.95	0.87	0.06	0.82
3	0.69	305.04	0.98	0.67	289.14	0.93	0.92	0.04	0.99	1.07	0.01	0.94
4	0.70	276.02	0.97	1.10	419.83	0.90	1.01	0.02	0.87	0.99	0.02	0.92
5	0.77	286.73	0.95	0.69	304.29	0.82	0.85	0.06	0.97	1.07	0.01	0.91
6	0.26	166.18	0.93	0.33	206.91	0.83	0.68	0.32	0.98	0.47	1.96	0.97
7	0.58	215.03	0.97	0.57	254.66	0.85	1.20	0.00	0.98	1.48	0.00	0.92
8	0.85	291.06	1.00	0.73	285.04	0.88	0.71	0.23	0.92	0.79	0.11	0.93
9	1.38	990.45	0.99	0.97	329.30	0.90	0.84	0.10	0.97	1.52	0.00	0.86
10	0.89	371.03	0.98	0.63	257.11	0.86	0.96	0.03	0.98	0.75	0.23	0.91
11	0.66	227.89	0.97	0.80	293.04	0.91	0.63	0.47	0.96	0.53	1.14	0.88
12	0.69	252.60	0.98	1.14	912.18	0.87	0.73	0.18	0.95	0.81	0.08	0.74
13	1.10	375.82	0.93	1.01	906.30	0.78	0.48	1.70	1.00	0.48	1.71	0.89
14	0.32	175.36	0.98	0.30	160.06	0.93	0.40	3.37	0.99	0.58	0.81	0.89
15	0.45	235.54	0.96	0.71	299.70	0.94	0.95	0.04	0.92	0.77	0.12	0.85
16	0.70	309.55	0.97	0.95	329.93	0.87	0.97	0.02	0.99	1.25	0.00	0.97
17	0.16	152.73	0.84	0.50	204.66	0.85	0.69	0.28	0.93	0.32	7.25	0.71
18	0.31	148.33	0.82	1.18	412.25	0.80	0.60	0.59	1.00	0.61	0.51	0.79
19	0.80	283.47	0.97	1.04	558.65	0.90	0.87	0.07	0.97	1.01	0.02	0.88
20	0.38	177.68	0.99	0.99	324.27	0.80	0.70	0.23	0.92	0.80	0.10	0.77

Table B.2 The exponents (n_v and n_s), the constants (k_v and k_s), and Spearman's rank correlation coefficients (r_v and r_s), obtained with RME and AME methods of 20 subjects when judging the discomfort of vibration (ψ_v) and the discomfort of noise (ψ_s). Second repetition.

2 nd	ψ_v RME			ψ_v AME			ψ_s RME			ψ_s AME		
No.	n_{vr2}	k_{vr2}	r_{vr2}	n_{va2}	k_{va2}	r_{va2}	n_{sr2}	K_{sr2}	r_{sr1}	n_{sa2}	k_{sa2}	r_{sa2}
1	1.38	1084.43	0.93	1.76	1649.89	0.91	1.48	0.00	0.98	1.46	0.00	0.96
2	0.36	188.32	0.94	0.49	199.89	0.76	0.51	1.31	0.96	0.86	0.07	0.92
3	0.77	337.16	1.00	0.71	288.73	0.88	0.94	0.04	0.97	0.73	0.24	0.90
4	0.94	364.05	0.97	1.30	561.50	0.85	1.09	0.01	0.98	1.13	0.01	0.95
5	0.77	284.10	0.99	0.72	345.06	0.86	0.88	0.06	0.98	0.97	0.03	0.95
6	0.31	192.27	0.93	0.38	180.73	0.80	0.82	0.10	1.00	0.51	1.40	0.97
7	0.77	221.48	0.97	0.57	250.10	0.71	1.51	0.00	0.96	1.21	0.00	0.95
8	0.69	238.08	1.00	0.81	278.00	0.91	0.74	0.18	0.98	0.74	0.17	0.92
9	1.40	1021.71	0.99	1.34	730.60	0.94	0.87	0.07	0.94	1.63	0.00	0.94
10	1.10	472.83	0.99	0.72	316.73	0.94	1.22	0.00	0.97	0.99	0.03	0.98
11	0.77	249.90	0.99	0.90	302.64	0.92	0.48	1.69	0.98	0.48	1.95	0.98
12	0.93	306.28	0.97	0.86	538.84	0.92	0.89	0.04	0.98	0.77	0.17	0.92
13	1.29	517.21	0.99	1.24	742.13	0.90	0.43	2.86	0.98	0.51	1.36	0.96
14	0.35	168.12	1.00	0.31	186.58	0.82	0.41	3.13	0.97	0.53	1.15	0.90
15	0.68	317.35	1.00	0.61	269.83	0.90	1.02	0.02	0.99	0.89	0.05	0.91
16	1.07	337.04	0.99	1.02	361.10	0.91	1.03	0.02	0.99	1.13	0.01	0.91
17	0.20	154.25	0.74	0.74	301.97	0.82	0.68	0.34	0.97	0.35	5.05	0.95
18	0.27	152.40	0.80	1.43	961.97	0.89	0.66	0.34	0.99	0.61	0.49	0.67
19	0.70	301.09	0.98	1.00	409.42	0.84	0.77	0.18	1.00	0.99	0.02	0.93
20	0.47	182.66	1.00	0.89	298.56	0.65	0.92	0.03	0.97	1.15	0.01	0.91

Table B.3 The exponents (n_v and n_s), the constants (k_v and k_s), and Spearman's rank correlation coefficients (r_v and r_s), obtained with RME and AME methods of 20 subjects when judging the discomfort of vibration (ψ_v) and the discomfort of noise (ψ_s). Third repetition.

3 rd	ψ_v RME			ψ_v AME			ψ_s RME			ψ_s AME		
No.	n_{vr3}	k_{vr3}	r_{vr3}	n_{va3}	k_{va3}	r_{va3}	n_{sr3}	K_{sr3}	r_{sr3}	n_{sa3}	k_{sa3}	r_{sa3}
1	1.68	1829.30	0.99	1.90	1414.79	0.85	1.56	0.00	0.98	1.42	0.00	0.92
2	0.35	178.43	0.95	0.40	202.71	0.83	0.57	0.79	0.98	0.69	0.25	0.91
3	0.83	358.80	0.98	0.73	299.57	0.88	0.95	0.03	0.98	0.90	0.06	0.92
4	0.96	346.30	1.00	1.20	457.70	0.73	1.10	0.01	0.97	0.74	0.17	0.85
5	0.80	306.11	0.98	0.74	308.49	0.88	1.00	0.02	0.96	0.90	0.05	0.92
6	0.29	181.55	0.94	0.30	154.24	0.70	0.69	0.31	0.98	0.44	2.57	0.89
7	0.85	264.91	0.99	0.82	247.59	0.90	1.40	0.00	0.97	1.20	0.00	0.86
8	0.73	238.75	0.93	0.68	306.98	0.90	0.69	0.24	0.98	0.70	0.25	0.94
9	1.26	738.81	1.00	1.47	960.60	0.95	0.95	0.04	0.99	1.76	0.00	0.98
10	1.16	498.32	0.99	0.75	331.22	0.97	1.41	0.00	1.00	0.92	0.04	0.88
11	0.71	229.17	1.00	0.82	348.81	0.91	0.45	2.29	0.99	0.48	1.82	0.90
12	0.89	297.10	0.95	1.03	570.75	0.86	0.85	0.07	0.94	0.79	0.15	0.93
13	1.08	374.18	0.99	1.03	473.67	0.89	0.38	4.25	0.99	0.52	1.34	0.96
14	0.22	141.95	0.98	0.31	171.10	0.96	0.43	2.81	0.99	0.57	0.78	0.99
15	0.78	353.85	0.99	0.80	308.18	0.81	1.10	0.01	0.98	0.80	0.11	0.83
16	1.24	516.34	0.98	0.98	546.97	0.96	1.10	0.01	0.99	1.07	0.01	0.93
17	0.23	139.21	0.86	0.66	229.31	0.96	0.67	0.35	0.95	0.36	4.92	0.86
18	0.19	135.31	0.76	1.58	1177.55	0.91	0.42	2.83	0.96	0.64	0.39	0.64
19	0.82	286.48	0.97	0.98	462.98	0.92	0.73	0.24	0.97	1.32	0.00	0.96
20	0.24	150.73	0.96	0.81	286.52	0.81	0.68	0.27	0.95	1.09	0.01	0.86

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