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Annoyance Caused by Railway Vibration and Noise in Buildings

by

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ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE

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ANNOYANCE CAUSED BY RAILWAY VIBRATION AND NOISE IN BUILDINGS

By Henrietta Victoria Carmel Howarth

This thesis is concerned with the annoyance caused by railway-induced building vibration and railway noise. A review of previous studies was conducted to examine current knowledge. The review enabled identification of areas in which there was insufficient information on which to base a prediction of the reaction to railway vibration and noise in buildings. Deficiencies in current knowledge formed the basis of a programme of experimental work which was conducted to investigate how the annoyance produced by railway-induced building vibration is affected by the number of trains, the vibration magnitude, the vibration frequency, the direction of vibration and the presence of noise.

Two laboratory experiments were concerned with how annoyance caused by railway-induced building vibration depends on the magnitude of vibration and on how often trains pass. A trade-off was determined between the number of trains and the vibration magnitude which indicated a fourth power relation between magnitude and duration. The relation supports the use of the vibration dose value as a method of vibration assessment.

Two further experiments were conducted to determine the subjective equivalence of noise and vibration and to investigate the interaction and combined effects of the two stimuli. The results suggest that vibration does not influence the assessment of noise but that the assessment of vibration can be increased or reduced by the presence of noise, depending on the relative magnitudes of the vibration and noise.

A fifth experiment was performed to investigate the influence on annoyance of vibration frequency, vibration magnitude and vibration direction. Vibration frequency weightings were determined to describe subjective response to whole-body vibration at low magnitudes such as occurs in buildings. The results indicate that the weightings in British Standard 6841 (1987) provide a reasonable approximation to the frequency dependence of response to whole-body vibration at low magnitudes.

In the final experiment the previous findings were combined to provide a general method of predicting the relative annoyance from complex conditions of railway vibration and noise. The method was shown to provide a more accurate prediction of the relative annoyance from railway vibration and noise than methods based on the influence of noise or vibration alone.

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CONTENTS

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Buildings in close proximity to railway tracks may vibrate during the passage of a train. Vibration is generated in the ground as the railway vehicle proceeds along the track. The motion may then be transmitted to the floors of buildings, causing the occupants to be exposed to vibration. Exposure to railway-induced building vibration usually occurs simultaneously with exposure to railway noise. This thesis describes a laboratory study concerned with the prediction of human response to combined vibration and noise within buildings adjacent to railways.

1.2 RAILWAY-INDUCED BUILDING VIBRATION

There are many sources of building vibration which may be indoor or outdoor activities. Indoor activities producing vibration within the building include walking, footfalls (going down stairs), doors banging and use of domestic appliances. Outdoor activities can generate vibration in the ground which may then be transmitted to buildings. Such sources include mining and quarry blasting, industrial plant machinery, overhead aircraft, construction equipment and road and railway traffic. Reaction of residents to the latter, railway-induced building vibration, is the main concern of the work documented in this thesis.

The characteristics of building vibration largely depend on the source of the vibration and on the vibration frequency response of the ground, building and floor. According to Griffin and Stanworth (1984), the characteristics of vibration transmitted to the ground by the passage of trains are influenced by various features of the train and track. Such features include the vehicle type (e.g. diesel multiple unit, electric multiple unit), vehicle load, train speed, wheel circumference, sleeper spacing and vehicle length. The type of ground affects the characteristics of the vibration. Transmission of vibration from the ground to the floor can alter the magnitude and the frequency content of the vibration in a manner which depends on the dynamic response of the floor. This is determined by its construction. Woodroof and Griffin (1987) conducted a field study, the results of which suggested that the frequency of the vibration recorded on the floors of houses during the passage of trains was often more influenced by the ground type than by the train type or structure of the building. However, they also suggested that the characteristics of the vibration produced can vary considerably in different parts of the same building.

Railway-induced building vibration is characterised by repeated short periods of vibration. The motion is complex and consists of events of different durations, occurring at different time intervals which may range from one per day to one in several minutes. Woodroof and Griffin (1987) recorded as many as 387 trains causing perceptible vibration in one 24-hour period at a single site. The vibration occurs at a range of magnitudes and frequencies, with most energy occurring at frequencies in the range 10 Hz to 50 Hz in the vertical axis. Railway-induced building vibration can occur, however, in several directions and usually occurs with simultaneous railway noise.

1.3 RAILWAY NOISE

Railway activities such as maintenance operations of the track and maintenance at freight yards and stations produce noise. Noise is produced by running trains and originates from the locomotive and from the interaction of the rail and wheel. Noise from running trains occurs intermittently and, like railway-induced building vibration, consists of variable frequencies, durations and levels. Residents exposed to noise from running trains are often simultaneously exposed to railway-induced building vibration. The laboratory experiments described in this thesis include investigations of the reaction of residents to noise from running trains when it is combined with railway-induced building vibration.

1.4 REACTION TO RAILWAY-INDUCED BUILDING VIBRATION AND RAILWAY NOISE

Reaction to the perception of railway-induced building vibration is affected by various factors. These may include ownership of the dwelling, fear of building damage, sleep disturbance, age of occupants and the presence of railway noise.

Only a small number of field studies have been conducted to determine the extent of annoyance in the community caused by building vibration from the passage of nearby trains. Fields and Walker (1980) conducted a survey, mainly concerned with community response to railway noise, from which they concluded that more than 55% of respondents living within 100 metres of a railway line noticed vibration from passing trains. They estimated that 2% of the population of

England were annoyed by railway noise and a fewer number (i.e. less than 2%) were bothered by railway-induced building vibration. Woodroof and Griffin (1987) estimated that less than 35% of residents living within 100 metres of a railway line noticed vibration from passing trains. They found that vibration was regarded as one of the least annoying aspects of the presence of the railway. Woodroof and Griffin extrapolated their data to the whole population of Scotland and estimated that 1.4% of adults noticed railway-induced building vibration. There is evidence to suggest that the extent of annoyance from railway vibration and noise in residential properties is less than the annoyance from road traffic vibration and noise. Morten-Williams et al (1978) conducted a broadly-based study throughout England and found that 8% of respondents were "bothered very much or quite a lot" by road traffic-induced vibration and 9% were bothered by road traffic noise. Comparison of the findings of Morten-Williams et al with those of Fields and Walker suggests that 4.5 times as many people are bothered by road noise as by railway noise and more than 4 times as many people are bothered by road vibration as by railway vibration. However, Fields and Walker suggested that 28% of the population of England were annoyed by road traffic vibration, i.e. more than 14 times as many as were annoyed by railway vibration.

Regardless of the extent of annoyance caused by vibration from railways, there exists a need for a method of evaluating the vibration which provides an indication of the reaction of residents to the stimuli. The method must allow for the effect on annoyance of different frequencies, durations, magnitudes and directions of vibration and for the presence of simultaneous noise.

1.5 METHODS OF ASSESSING RAILWAY-INDUCED BUILDING VIBRATION

1.5.1 Standards

The first publication from the International Standards Organisation concerned with the assessment of building vibration with respect to human exposure was the Draft Addendum 1 to ISO 2631 (1980), "Guide to the evaluation of human exposure to vibration and shock in buildings (1 Hz to 80 Hz)." This draft standard provided separate base curves for vertical and horizontal vibration (root-mean-square acceleration as a function of frequency) which were indicated as corresponding to the general range of vibration perception. The acceptable magnitudes of vibration in buildings were determined from the multiplication of the base curves by given factors which depended on the use of the building, the time of exposure (day or night) and whether the vibration was continuous or intermittent. The same base curves are provided in British Standard 6472 (1984) but higher multiplying factors are given for impulsive vibration in residential buildings and improved methods of measuring these motions are offered. International Standard 2631/DAD 1 (1980) has been superseded by ISO/DIS 2631/2 (1985) which proposes essentially the same methods of evaluating building vibration as BS 6472 (1984).

1.5.2 Field Studies

An extensive field study was conducted by Woodroof and Griffin (1987) which involved measurement of vibration in residential properties within 100 metres of a railway line and a social survey designed to determine the reaction of residents to railway-induced building vibration. An objective of the study was to determine a method of assessing building vibration which could provide an indication of community response. Correlations between subjective response and the severity of the vibration were investigated, where the severity of the vibration was given by 90 different objective measures. These involved different frequency weightings, integration times and averaging procedures. The results showed that although the subjective response of residents was correlated with the number of trains passing in 24 hours, the response was not correlated with any of the physical characteristics of the vibration in their homes. Woodroof and Griffin concluded that this result arose because railway-induced building vibration did not cause significant annoyance in the community as a whole. They proposed that there may have been individuals who were annoyed but they were not numerous enough to influence the results of such a social survey which involved a pseudo-random sample of residents. The field study was, therefore, not successful in determining a method of assessing building vibration which could provide an indication of subjective response.

1.5.3 Laboratory Studies

There remains a need for an objective method of assessing building vibration so that reaction may be predicted and recommendations and limits of vibration may be set. Ideally, determination of a means of assessing vibration which provides the best indication of community response should involve a study in the community. But in the light of the results of their field study, Woodroof and Griffin concluded that future investigations should be conducted in the laboratory. An advantage of laboratory investigations is that conditions may be controlled in a manner which allows investigation of the effect of one or more variables. It may be argued that reaction to stimuli in the laboratory may not be identical to reaction to the same stimuli in the community. However, it seems likely that the manner in which annoyance is dependent on the different variables characterising building vibration will be the same in the two environments.

Although many laboratory studies have been conducted to investigate the influence of different vibration variables on the reaction to whole-body vibration, most of the studies have involved motions at magnitudes much greater than would be experienced in buildings. One of the few laboratory studies which was concerned with reaction to railway-induced building vibration was conducted by Woodroof, Lewis and Griffin (1983). Two laboratory experiments were conducted which involved the exposure of men and women to reproductions of vibration recorded in houses during the passage of nearby trains. The subjective reaction was correlated with 108 objective measures of assessment. It was concluded that the best subjective method involved the vertical axis frequency weighting given by ISO 2631/DAD 1 (1980) combined with a fourth power measure of vibration dose ($_0\int^T a^4(t)\, dt$, where a(t) is the frequency weighted acceleration). The study did not provide information on the response to horizontal motion nor on the effect of simultaneous noise. Further work is required to investigate evidence from other studies that the ISO 2631 vertical (z-axis) frequency weighting underestimates sensitivity to high frequencies.

1.6 METHODS OF ASSESSING RAILWAY NOISE

A method of evaluating railway noise, which provides an indication of the annoyance which may be produced must take into consideration the influence of the variable characteristics, i.e. duration, frequency and level of sound. Appendix 5.1 provides a discussion of the current methods of evaluating noise in the community and their application to the assessment of railway noise. The dependence of subjective response to noise on duration, frequency and level of sound is considered in the discussion.

1.7 OBJECTIVES OF THE RESEARCH

The main objective of the research reported in this thesis was to determine a method of assessing railway-induced building vibration and railway noise with respect to the annoyance which may be produced by the stimuli. This involved identification of areas of deficiency in current knowledge. These areas then formed the basis of a programme of experimental work. The findings of the laboratory experiments were combined to provide a method of predicting the relative annoyance caused by simultaneous vibration and noise from railways.

The thesis reports one of very few laboratory investigations concerned with human response to whole-body vibration at magnitudes just above the threshold of perception. Only a small number of previous laboratory investigations have involved human exposure to vibration stimuli which may be experienced in the community. Most previous studies have involved artificial vibration stimuli, such as sinusoidal motion. The present work involved the reproduction of motion which occurred in houses. It is the only laboratory investigation which has involved exposure of men and women to simultaneous vibration and noise recorded in houses during the passage of nearby trains.

This thesis describes a comprehensive study in which laboratory experiments were conducted to investigate not only the effect of each of the variables of railway-induced building vibration on subjective response (duration, frequency, direction and magnitude) but also the response to combined railway vibration and noise.

1.8 ORGANISATION AND CONTENT OF THE THESIS

This thesis is divided into eight chapters. An introductory chapter is followed by a literature review and then five chapters describing experimental work. The final chapter provides a summary of the conclusions of each experiment. It describes the application of the results and details recommendations for future research. The content of each chapter is outlined below.

Chapter 1

This chapter provides an introduction to the subject of the annoyance caused by railway-induced building vibration and railway noise. An outline of the thesis is provided. Finally, the conventions adopted are described.

Chapter 2

A review is provided of previous studies concerned with the reaction to whole-body vibration. The chapter is divided into eight parts which relate to the effect of different vibration variables on the reaction to whole-body vibration.

Chapter 3

The equipment employed in the laboratory experiments is described in this chapter.

Chapter 4

Two experiments are described which were conducted to determine how annoyance produced by railway-induced building vibration depends on the magnitude of the vibration and on how often trains pass.

Chapter 5

This chapter describes the third and fourth experiments. The third experiment was conducted to find the subjective equivalence of railway vibration and noise. The fourth experiment investigated the interaction and combined effects of vibration and noise from railways.

Chapter 6

The fifth experiment was conducted to determine the frequency and magnitude dependence of the annoyance produced by vertical and horizontal whole-body vibration at low magnitudes. The relative importance of vertical and horizontal motion was also determined.

Chapter 7

The final experiment is described in this chapter. The findings of the previous experiments were combined to assess a method of predicting the annoyance produced by different reproductions of railway vibration combined with simulated railway noise.

Chapter 8

A summary of the findings of the laboratory investigations is provided in the final chapter. In the light of these findings, procedures are recommended for the assessment of railway vibration and noise. Application of these procedures is described. Finally, the chapter outlines proposals for future research.

1.9 TERMINOLOGY

The axis of vibration transmitted to occupants of buildings depends on the direction of the vibration in the building and the posture of the exposed person (sitting, standing or recumbent). This thesis distinguishes between the three translational axes of vibration by adopting the conventions commonly used in biodynamics and specified in the International Standard ISO 2631/DAD 1 (1980). The conventions, which are illustrated in Figure 1, relate to an orthogonal co-ordinate system having its origin at the human heart. Motion in the foot (or buttocks)-to-head axis is defined as z-axis motion; motion in the fore-and-aft (back-to-chest) axis is defined as x-axis motion and motion in the lateral (left side-to-right side) axis is defined as y-axis motion. This means that vertical motion is described as z-axis vibration of sitting and standing persons and as x-axis vibration of recumbent persons. Similarly, horizontal motion is described as x- or y-axis vibration of sitting and standing persons and as z- or y-axis vibration of recumbent persons.

1.10 UNITS

In this thesis, frequency is expressed in hertz (Hz), which is the name, by international agreement, given to the number of repetitions of a periodic phenomenon in one second. The vibration acceleration is expressed in units of metres per second per second (ms^{-2}). When referring to data from other studies, acceleration is sometimes expressed in units of "g" (acceleration due to gravity). One "g" is equal to 9.81 ms^{-2}.

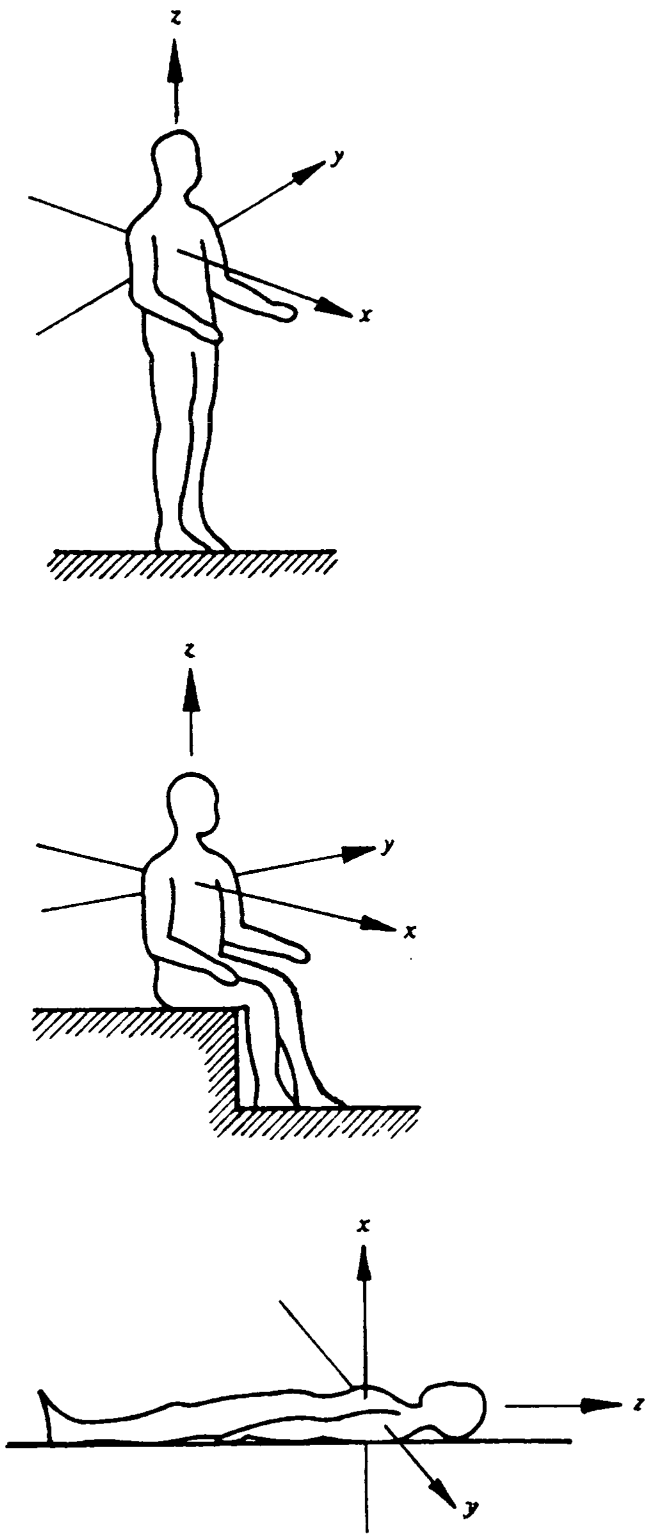

Figure 1 Directions of the co-ordinate system for human exposure to whole-body vibration as defined in ISO 2631/DAD 1 (1980).

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

2.1.1 Aim

This literature review examines the current knowledge of the influence of vibration characteristics on human response. The review seeks to consider whether existing information on the effects of whole-body vibration is applicable to railway-induced building vibration. The purpose of this chapter is to identify areas in which there is insufficient knowledge to provide a means of quantifying vibration produced during the passage of nearby trains with respect to annoyance.

2.1.2 Structure

The review is divided into seven parts, each of which is concerned with a different variable characterising railway-induced building vibration. Each section relates directly to one or more of the experimental chapters:

2.2 *The effect of magnitude on the subjective response to whole-body vibration*

This section reviews studies which have been conducted to determine the growth function of the subjective magnitude of vibration as a function of the objective magnitude. The effect of magnitude on human response is relevant to all the experiments conducted.

2.3 *The time dependency of subjective response to whole-body vibration*

The findings of studies which have sought to determine the influence of vibration duration are compared. This section of the review relates particularly to the first two experiments which are described in Chapter 4.

2.4 *Perception thresholds of vertical and horizontal whole-body vibration*

Perception is a prerequisite for annoyance to result from railway-induced building vibration and therefore knowledge of the thresholds of perception is a necessity in the evaluation of railway vibration with respect to human response. Perception thresholds for translational vibration determined in previous studies are compared.

2.5 A comparison of perception thresholds and comfort contours

The frequency dependence of perception thresholds and equal comfort contours determined in previous studies are compared. The findings are directly related to Experiment 5 which is described in Chapter 6.

2.6 The subjective equivalence of noise and whole-body vibration: a review of previous investigations

This section is concerned with studies conducted to investigate the relative importance of noise and vibration and relates to Experiments 3, 4 and 6.

2.7 A review of studies of the reaction to simultaneous noise and vibration: interaction and combined effects

This section compares the findings of investigations of the combined effects of noise and vibration and the interaction of the subjective reaction to the noise and vibration. The section relates to Experiments 4 and 6 (see Chapters 5 and 7).

2.2 A REVIEW OF INVESTIGATIONS OF THE EFFECT OF MAGNITUDE ON THE SUBJECTIVE RESPONSE TO WHOLE-BODY VIBRATION

2.2.1 Introduction

Experimental procedures for determining subjective response to whole-body vibration include magnitude estimation, magnitude production and scaling methods. The procedures enable vibration stimuli to be ranked in order of the discomfort produced by each stimulus. To determine how much greater is the subjective reaction to one stimulus than to another, it is necessary to know the psychophysical relation between the subjective magnitude of a stimulus, ψ, (e.g. magnitude estimation, equivalent magnitude or rating) and its objective magnitude, φ (e.g. acceleration magnitude of the vibration stimulus). The analogy in psychoacoustics is the relation determined by Stevens (1955) to equate loudness, L, and sound pressure, p. As a psychophysical power function, the relation is written as:

$$L = kp^{0.6}$$

where k is a constant.

In terms of the number of decibels, N, above reference level, the loudness, L, is given by:

$$\log_{10} L = 0.03\ N + S$$

where S is the spectrum parameter.

This section reviews experiments which have been conducted to determine the growth function, n, relating the subjective magnitude, ψ, of a stimulus to its acceleration magnitude, φ, in the power law form, $\psi = k\varphi^n$, where k and n are constants. The studies have been grouped according to the experimental technique employed.

2.2.2 Corrected Ratio Method (Miwa, 1968a)

Miwa (1968a) employed the corrected ratio method to determine the psychophysical scale for vibration stimuli. The method was devised by Garner (1954) to obtain the loudness scale in psychoacoustics and involved fractionation and equisection judgements. Ten male subjects adopted a seated posture and were exposed separately to vertical and fore-and-aft whole-body vibration at 5, 20 and 60 Hz. Fractionation judgements were made by repeated presentations to the subjects of a reference stimulus of fixed magnitude followed by a stimulus of variable magnitude at the same frequency and then a rest period. The reference stimulus, test stimulus and rest period each lasted for four seconds. The magnitude of the variable stimulus was adjusted by the experimenter in ascending and descending series until the subject indicated that the variable stimulus was felt to be half the magnitude of the reference stimulus. The procedure was repeated with six magnitudes of reference stimulus from 17 to 67 VGL (VGL is a logarithmic unit devised by Miwa to describe a frequency weighted magnitude of a stimulus). Equisection judgements required the subject to determine the magnitude of vibration half-way between two stimuli. The subjects then found the mid-point of the two halves. Finally, they bisected the three overlapping intervals between the two original stimuli. The judgements were carried out in the descending system by presentation of the stimuli in the order: upper fixed magnitude stimulus, lower variable magnitude stimulus and then a rest period. In the ascending system the lower stimulus was presented first and was of variable magnitude, the upper stimulus was presented second and was fixed. Linear regression of the acceleration magnitude, φ, the subjective magnitude, ψ, on log-log coordinates was conducted to determine the exponent, n. Miwa found that the growth function was independent of frequency but depended on the magnitude of the stimuli. The relation was determined in logarithmic form, however, as a power function the results were $\psi = k\varphi^{0.60}$ for stimuli of magnitude less than 1 ms^{-2}, and $\psi = k\varphi^{0.46}$ for stimuli of magnitude greater than 1 ms^{-2}. The corrected ratio technique is very complicated and introduces many problems which do not occur with other techniques. According to Fothergill and Griffin (1977), it is for this reason that the method has not been used more.

2.2.3 Magnitude Estimation and Magnitude Production

This section reviews studies which have employed either magnitude estimation or magnitude production, or a combination of both methods, to investigate the value of the exponent, n, in the power function, relating subjective magnitude, ψ, and acceleration magnitude, φ. The method of magnitude estimation requires the subject to assign numbers to a test stimulus to indicate its subjective magnitude as a multiple of a reference stimulus. The method of magnitude production requires the subject to adjust a test stimulus to the magnitude which produces a sensation having a specified relation to a reference stimulus.

2.2.3.1 Shoenberger and Harris (1971)

Shoenberger and Harris (1971) employed the method of magnitude estimation to determine the exponents of psychophysical power functions for the subjective magnitude of vertical whole-body vibration at seven frequencies. Twenty male subjects compared a reference stimulus at 0.32 ±g (3.13 ms^{-2}) with seven magnitudes of test motion from 0.08 ±g to 0.56 ±g (0.78 to 5.5 ms^{-2}) at the same frequency. The reference stimulus was presented after every third stimulus. Seven frequencies, in the range 3.5 to 20 Hz, were investigated. Figure 2.2.1 is adapted from Shoenberger and Harris (1971) and shows the magnitude estimates as a function of the acceleration magnitude on log-log coordinates for each frequency of motion. The gradient of the regression line varied from 0.86 to 1.04.

The authors hypothesised that the exponent in the power function describing the effect of magnitude is frequency dependent. The hypothesis was based on the assumption that the threshold of perception is constant over the frequency range considered and that motions at frequencies at which the body is most sensitive are judged intolerable at lower magnitudes than at other frequencies. They suggest this implies the exponent for frequencies at which the body is most sensitive must be greater than at other frequencies, as the allowable acceleration range is smaller.

Analysis of variance was performed to determine whether the exponent was frequency dependent. Table 2.2.1 shows the gradient of the regression line for each frequency determined from the mean magnitude estimates. The slope for 5 Hz was significantly greater than the slope for 7, 15 and 20 Hz. The slope for 7 Hz was significantly less than for 11 Hz ($p < 0.05$). Shoenberger and Harris suggested the results generally support their hypothesis since the exponent was significantly larger at 5 Hz, which is one frequency at which the body is most sensitive. However, the hypothesis was not supported at 7 Hz. The exponent was smallest at 7 Hz although the sensitivity at this frequency is also high. The foundation of the hypothesis is in doubt since there is evidence to suggest that the threshold of perception is not the same for all frequencies (e.g. Benson and Dilnot (1981), Parsons (1981)). It is possible that different sensory mechanisms are responsible for perception and discomfort, so it cannot be assumed that the effect of magnitude on discomfort from whole-body vibration can be linearly related to the perception thresholds. The value of the exponent did not vary greatly between frequencies, however, there was large intersubject variability. The mean slope averaged across all frequencies was 0.94.

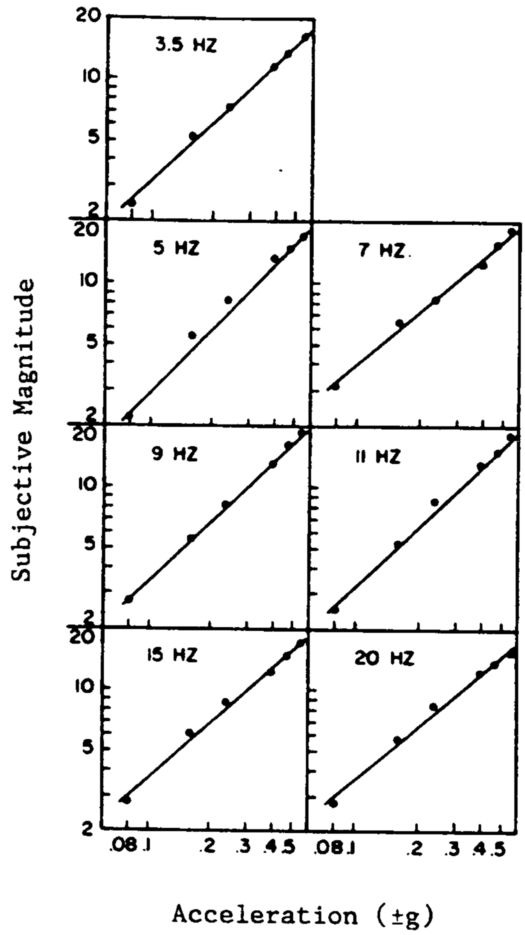

Figure 2.2.1 Regression of magnitude estimate as a function of acceleration. Adapted from Shoenberger and Harris (1971).

Frequency (Hz)	3.5	5	7	9	11	15	20
Gradient	0.95	1.04	0.86	0.97	0.98	0.91	0.87

Table 2.2.1 Gradients of the regression lines of logarithm of magnitude estimate as a function of logarithm of acceleration determined by Shoenberger and Harris (1971).

2.2.3.2 Jones and Saunders (1974)

The method of magnitude estimation was employed by Jones and Saunders (1974) to investigate the subjective magnitude of vertical sinusoidal whole-body motion of frequencies between 5 and 80 Hz. Thirty seated men, thirty seated women and ten standing men were presented alternately with two sinusoidal vibration stimuli of the same frequency. The acceleration magnitude ranged between 0.35 to 1.4 ms^{-2} r.m.s. at 5 Hz and 2.1 to 11.8 ms^{-2} r.m.s. at 80 Hz. The subjects indicated how many times greater the second stimulus felt than the first. Within subject variability at 20 Hz was investigated with six male subjects by ten repetitions of the experiment with at least one day between repetitions. Finally, 23 males and 15 females repeated the experiment at 20 Hz one to two months after the first session, in order to determine the stability of the results.

Linear regression analysis of individual and pooled data was conducted between the magnitude estimation and the acceleration magnitude on log-log coordinates. Jones and Saunders showed the regression analysis results for pooled data only. However, they considered that the large variability of individual results and the variation in the growth function between individuals was such that it was sufficiently accurate to summarise the results in terms of average growth functions for each frequency of motion for men and women separately. The average growth function for the 30 men and 30 women adopting a seated posture varied from 0.88 to 0.99. For the ten standing men the average growth function varied from 0.94 to 1.03. Analysis of variance conducted on individual straight line gradients showed that in only a few cases, usually involving 40 Hz motion, was the exponent significantly different between frequencies or between men and women. The results were stable over a period of one to two months. Jones and Saunders concluded that a single power law would adequately describe the subjective magnitude of whole-body vibration and therefore they combined all their results to determine the relation $\psi = 1.315\varphi^{0.93}$ for vertical sinusoidal motion in the frequency range 5 to 80 Hz.

2.2.3.3 Clarke and Oborne (1975a)

Clarke and Oborne (1975a) employed magnitude estimation and magnitude production methods in a study comparing techniques for obtaining the power law for subjective magnitude of vertical whole-body vibration. The experiment was conducted at six frequencies of motion between 3 and 50 Hz. The approximate range of the acceleration magnitude was between 0.3 and 5.0 ms^{-2} r.m.s. The method of magnitude estimation was employed with 12 standing subjects and involved the presentation of a reference stimulus assigned a value corresponding to its subjective magnitude. The subjects were then presented with a test stimulus and were asked for a numerical assessment of the motion. The method of magnitude production involved eight standing subjects and consisted of fractionation (halving) and multiplication (doubling) techniques. The subjects were presented alternately with a fixed reference stimulus and a variable test stimulus and were asked to adjust the variable stimulus to the magnitude which produces half or double the sensation of the reference stimulus. Table 2.2.2 is adapted from Clarke and Oborne (1975a) and shows the mean power law exponent of the individual results obtained by the three methods at six of the frequencies investigated.

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	Mean 0.96	Mean 1.38

Table 2.2.2 Power law exponents determined by Clarke and Oborne (1975a) from three experimental methods.

Table 2.2.2 shows that fractionation and multiplication techniques tended to result in higher exponents than magnitude estimation. The scatter of the results for the method of magnitude estimation increased as the difference between the magnitude of the test and reference stimuli increased. The scatter was greater when magnitude estimation was employed than with fractionation or multiplication. According to Clarke and Oborne these effects were predicted by Poulton (1968) who suggested the exponents depend on the range of experimental values. Magnitude estimation resulted in a ratio of up to 3:1 for the individual range of exponents at a given frequency, compared with a ratio of 1.25:1 when fractionation or multiplication was employed.

Clarke and Oborne compared the results of fractionation and multiplication techniques and found that fractionation consistently results in lower exponents than multiplication. They explained the difference by a time effect, whereby the second stimulus is consistently matched high. The effect was indicated in experiments where subjects matched two stimuli at the same frequency. Clarke and Oborne suggested that it would be appropriate to take the mean of the fractionation and multiplication exponents to correct for this effect. However, the resulting exponents were still higher than the exponents obtained by magnitude estimation. They concluded that magnitude estimation should be viewed with caution in the determination of the exponent in the power law for the subjective magnitude of vibration.

Magnitude estimation resulted in a mean exponent of 0.93 compared with the mean exponent of 1.17 from magnitude production. Despite the uncertainties expressed about magnitude estimation, the method resulted in a similar value of the exponent to that obtained from magnitude production. No statistical analysis was given to show whether the difference between the results of the two methods was significant.

2.2.3.4 Leatherwood and Dempsey (1976a)

Subjective ratings of discomfort and intensity were correlated with four psychophysical relationships in a study by Leatherwood and Dempsey (1976a) in which they exposed 48 seated subjects to vertical sinusoidal vibration at ten frequencies between 2 and 29 Hz and nine magnitudes between 0.35 and 3.1 ms^{-2} r.m.s. Subjects compared reference and test motions of the same frequency. Half the subjects were asked to indicate the relative discomfort of the test motion and the other half were asked to indicate its relative intensity. The individual geometric and arithmetic mean results at each frequency were correlated with four psychophysical relationships relating subjective reaction, ψ, and acceleration magnitude, φ. The relations were $\psi = a\varphi^b$, $\psi = a + b \log \varphi$, $\psi = a\ 10^{b\varphi}$ and $\psi = a + b\varphi$, where a and b are constants. Leatherwood and Dempsey proposed a linear law ($\psi = a + b\varphi$) to describe the relationship between subjective ratings of intensity or discomfort. This proposal was based on group and individual analysis which showed that in most cases there was no significant difference between correlations with the four psychophysical relationships. Leatherwood and Dempsey selected a linear law ($\psi = a + b\varphi$) for the practical advantages of its simplicity. They suggested the variability of the data did not justify the use of the more complex power law ($\psi = a\varphi^b$). The power relationship resulted in larger correlation coefficients than the other three methods, although the correlation was only significantly larger than the exponential method ($\psi = a\ 10^{b\varphi}$). The mean value of the exponent, b, in the power law was 1.24 for evaluation of discomfort and 1.14 for evaluation of intensity. Figure 2.2.2 shows the variation with frequency of the mean exponent, b, in the power law obtained from individual assessment of discomfort. The authors reported variation of the exponent with frequency and also large variability of the exponent between subjects at each frequency. The t-test was applied at each frequency to determine if there was a significant difference between subjective ratings of discomfort and intensity. The difference was significant at three of the ten frequencies: 17, 20 and 23 Hz.

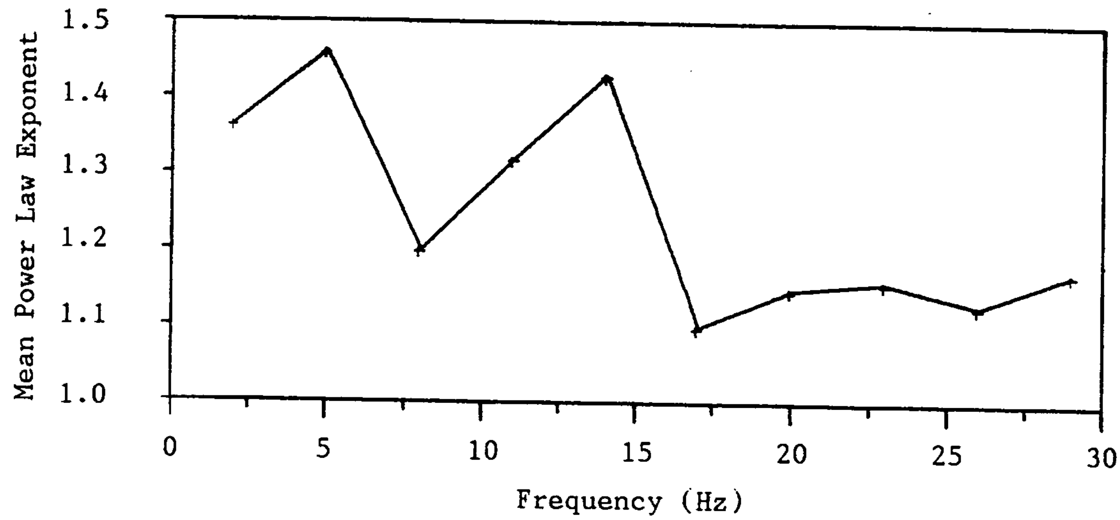

Figure 2.2.2 Mean power law exponent for discomfort as a function of frequency. Adapted from Leatherwood and Dempsey (1976a).

2.2.3.5 *Fothergill and Griffin (1977)*

The methods of magnitude production and magnitude estimation were compared in a study by Fothergill and Griffin (1977) in which they investigated the subjective magnitude of 10 Hz vertical whole-body vibration. Magnitude estimation involved the alternate presentation of a 10 Hz reference vibration at 0.7 ms^{-2} r.m.s. and a 10 Hz test motion at one of seven magnitudes between 0.175 and 2.8 ms^{-2} r.m.s. The two stimuli were alternated until the subject indicated the ratio of the "strengths" of the two stimuli. Magnitude production involved the alternate presentation of a 10 Hz reference motion fixed at 0.7 ms^{-2} r.m.s. and a 10 Hz variable test motion. The subject adjusted the test motion to the magnitude at which the ratio between the "strengths" of the two stimuli was one of seven different values from $^1/_4$ to 4. Regression lines and the corresponding correlations were determined for grouped and individual data for the two methods. The correlation coefficients of the individual regression lines were equal to or greater than 0.9. Table 2.2.3 is adapted from Fothergill and Griffin (1977) and shows the individual values of the exponent, n, in the psychophysical power law for vibration, $\psi = k\varphi^n$. For all subjects the exponent, n, was greater and varied more for magnitude production than for magnitude estimation.

Subject	1	2	3	4	5	6	7
Magnitude estimation	1.22	1.07	0.91	0.94	1.39	1.37	1.18
Magnitude production	2.08	1.20	1.75	1.43	1.48	2.12	1.47

Subject	8	9	10	11	12	13	14
Magnitude estimation	1.02	1.20	1.14	1.13	1.05	0.82	1.32
Magnitude production	1.97	1.47	2.80	1.36	3.20	0.93	1.41

Table 2.2.3 Individual values of the exponent determined by Fothergill and Griffin (1977) using magnitude estimation and magnitude production techniques.

The mean value of the exponent, calculated by linear regression analysis using all the data, was 1.12 for magnitude estimation and 1.64 for magnitude production. This compares well with the values of 1.13 and 1.75, for magnitude estimation and magnitude production respectively, which were determined from the mean exponents of individual data. A satisfactory explanation for the difference in the mean exponent for the two methods was not provided by Fothergill and Griffin. They refer to several explanations offered by Stevens and Greenbaum (1966) in which they concluded that magnitude estimation provides an adequate lower bound for the value of the exponent but it requires magnitude production to provide an adequate upper bound. Fothergill and Griffin concluded that it is sufficiently accurate to assume a value of unity for the exponent in the power function and that the large differences in the value of the exponent between individuals suggest that determination of an exact value is unnecessary. These conclusions are supported by studies by Jones and Saunders (1974), Clarke and Oborne (1975a) and

Leatherwood and Dempsey (1976a) which also showed large variations in the value of the exponent between individuals.

2.2.3.6 *Hiramatsu and Griffin (1984)*

Hiramatsu and Griffin (1984) sought to determine the exponents of psychophysical power functions for the effect of magnitude and duration of vibration. The method of magnitude estimation was employed, using no reference motion. Eighteen subjects were presented with vertical whole-body vibration at 8 Hz, consisting of 25 combinations of five magnitudes in the range 0.5 ms^{-2} r.m.s. to 2.5 ms^{-2} r.m.s. and five durations between 2 and 50 seconds. The numbers from each subject were normalised about the mean value from all subjects. Figure 2.2.3 shows the normalised magnitude estimates as a function of acceleration magnitude for each duration. The rate of increase in discomfort as a function of magnitude was determined by averaging across all durations. The value of the exponent in the psychophysical power function was 0.96, with 90% confidence limits of 0.90 and 1.03.

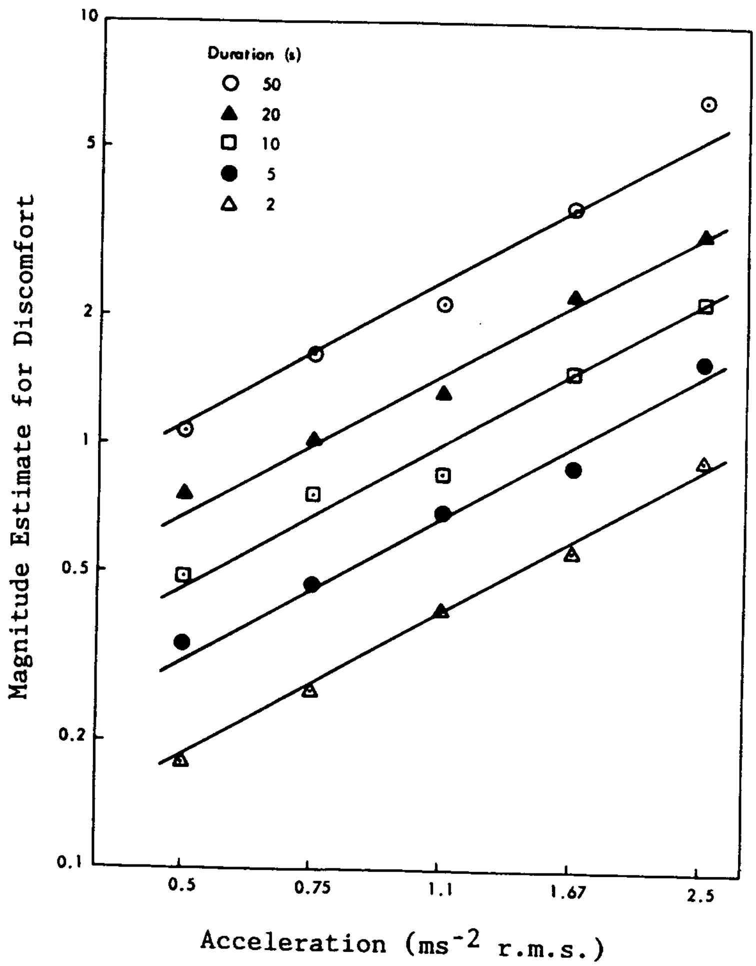

Figure 2.2.3 Magnitude estimates for vibration magnitudes and durations. Adapted from Hiramatsu and Griffin (1984).

A second experiment was conducted to determine the subjective equality of 16 "non-steady" vibrations and the results were correlated with three objective measures of evaluating whole-body vibration. The experiment included the presentation of 8 Hz "steady" vibration at four magnitudes to 15 subjects. Linear regression was conducted to obtain a value of 1.20 for the exponent in the power function describing the effect of vibration magnitude. Hiramatsu and Griffin suggested that a higher exponent was obtained in the second experiment because the range of stimuli employed was smaller (see Stevens, 1975).

2.2.4 Rating Methods (Oborne and Clarke, 1974)

Equal comfort contours were determined in a study conducted by Oborne and Clarke (1974) using the rating method. Twelve male subjects were presented with 75 vertical sinusoidal vibration stimuli consisting of eleven frequencies between 3 and 80 Hz and a range of magnitudes between 0.1 and 10 ms^{-2} r.m.s. Subjects rated each stimulus by marking a 10 cm line labelled from 0 to 10 at intervals of 2, where 0 was indicated as corresponding to "smooth" and 10 corresponded to "rough". The mean rating, determined from the distance from the smooth end, is shown as a function of acceleration on linear-logarithmic coordinates for each frequency in Figure 2.2.4, which is adapted from Oborne and Clarke (1974). The regression lines, determined for each frequency, are also shown in the figure. The regression equations were employed to determine equal comfort contours corresponding to four distances along the rating line.

If the mean ratings were shown on log-log or linear-linear coordinates the gradient of the curves would be seen to decrease at high magnitudes. This may be explained by an end effect of the rating scale. At frequencies in the range 5 to 15 Hz, the mean rating at the highest magnitude was greater than 8 on the 10 cm scale. It is likely that some of the subjects reached the end of the scale for stimuli at high magnitudes, so that the curve flattened out. At frequencies greater than 15 Hz and at 3 Hz the mean ratings were all less than 8 and the ratings tended to form a curve on linear-logarithmic coordinates. The correlation coefficients were smaller at these frequencies than between 5 and 15 Hz when the ratings were higher. The presence of an end effect may explain why the regression equation relating subjective magnitude and acceleration was not determined in the form of a power function.

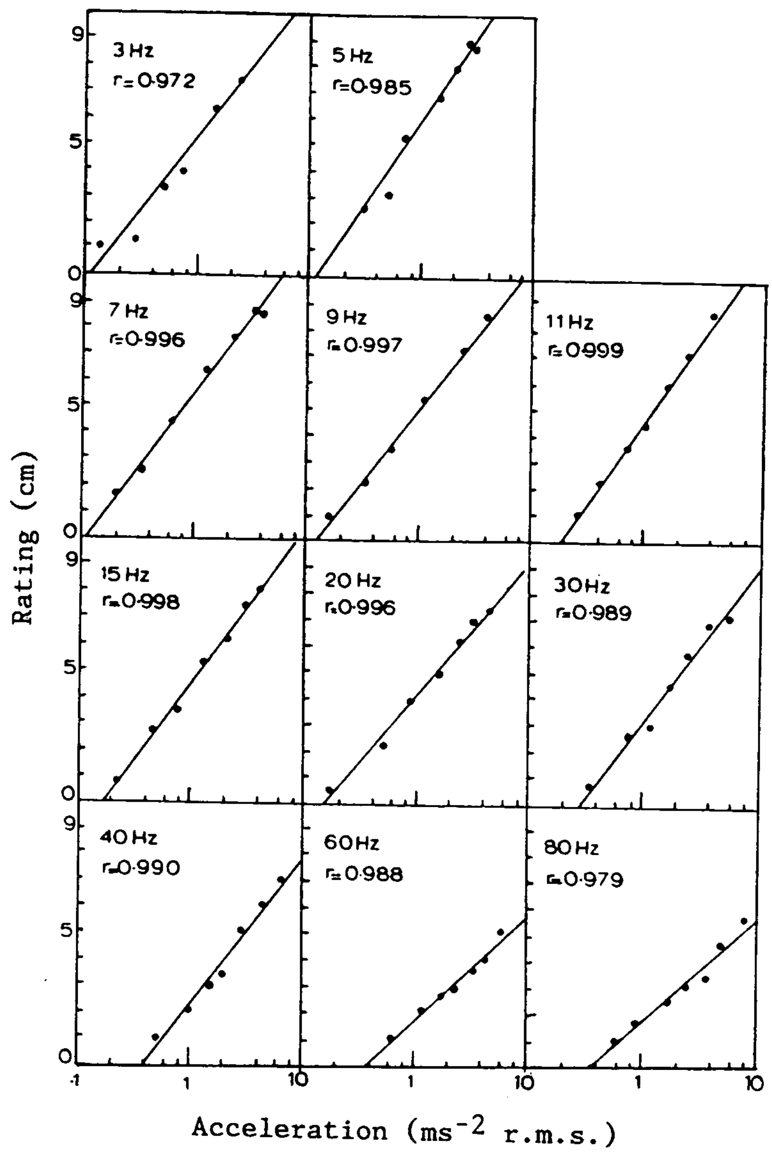

Figure 2.2.4 Regression lines of mean rating as a function of acceleration magnitude. Adapted from Oborne and Clarke (1974).

2.2.5 Cross-Modality Methods

2.2.5.1 Versace (1963)

Cross-modality matching was employed by Versace (1963) to determine the relation between subjective magnitude and acceleration magnitude of whole-body vibration. A single subject was exposed to vertical motion consisting of five frequencies between 1 Hz and 7 Hz and acceleration magnitudes in the range 0.2 ms^{-2} to 1.0 ms^{-2} rms. The subject adjusted random noise, received through headphones, to the level which produced the same reaction as the vibration stimuli. Noise level was shown as a function of acceleration on log-log coordinates for each frequency of motion. The assumption was made that the exponent relating loudness to sound pressure is 0.6. This relation was employed to determine an exponent for vibration in the range 0.90 to 1.30. The results compared well with studies reviewed in this section, however, emphasis cannot be placed on a study which involved only one subject.

2.2.5.2 Hempstock and Saunders (1973)

The exponent in the power function for the subjective magnitude of vibration was determined from the equivalence between noise and vibration in a study by Hempstock and Saunders (1973). Cross-modality matching was employed by seated subjects to adjust the magnitude of a vibration stimulus to the level which caused the same reaction as a fixed noise stimulus and to adjust the level of a noise stimulus to match a fixed vibration stimulus. The noise stimulus was $^1/_3$-octave band random noise centred at 2 kHz. Five magnitudes of vibration from 0.05 to 0.4 g r.m.s. (0.49 to 3.9 ms^{-2} r.m.s.) and six frequencies of motion from 6 Hz to 80 Hz were presented when the noise stimulus was variable. With vibration as the variable stimulus, 5 Hz to 80 Hz motion was investigated and the noise was presented at five levels in the range 60 to 100 dB(A). The direction and type of motion was not reported.

For the condition in which noise was the variable stimulus, the results from nine subjects were presented in the form:

$$P = S \log a + b$$

where P is the sound pressure level,
a is the root-mean-square acceleration,
b is a constant,

$$S = \frac{20m}{n},$$

where n is the growth function for noise,
m is the growth function for vibration.

For the condition in which vibration was the variable stimulus, the results from 18 subjects were determined in the form:

$$\log a = S_1 P + b_1$$

where b_1 is a constant and $S_1 = \frac{n}{20m}$.

The growth function for vibration, m, at each frequency was determined by making the assumption that the growth function, n, for noise is 0.6. The growth function for vibration varied from 0.47 to 0.60 when noise was the variable stimulus and from 1.11 to 1.43 when vibration was variable stimulus. The authors concluded that, when the cross-modality method was employed, the exponent depended on which stimulus was variable. The average value of the exponents from the two methods was determined at each frequency and ranged from 0.85 to 1.00, with an overall average of 0.89. The value of the exponents, determined by combining the two methods, compared well with other studies. If a subject required the variable stimulus to be increased to a magnitude greater than the capabilities of the apparatus, the result was discarded. The authors did not state at which conditions this occurred, so it is not possible to determine whether the results were biased by the elimination of some data.

2.2.6 Discussion and Conclusions

The studies reviewed have shown that the relation between the subjective magnitude, ψ, of a stimulus and the objective magnitude, φ, can be described by a power function of the form $\psi = k\varphi^n$, where k and n are constants. Miwa (1968a) determined the exponent, n, to be 0.60 for stimuli of magnitudes less than 1 ms^{-2} and 0.46 for stimuli of magnitudes greater than 1 ms^{-2}. This value of the exponent is smaller than determined by the other studies. The corrected ratio method which was employed introduced many difficulties. Jones and Saunders (1974) found a lack of consistency of individual results and large variations in the growth function between individuals. Considering this variability they decided that it was sufficiently accurate to summarise the results in terms of an average growth function of 0.93. A large variability between subjects was also found in other studies.

Clarke and Oborne (1975a) compared magnitude estimation and magnitude production (fractionation and multiplication) techniques and found that the intersubject variability in the value of the exponent was greater when magnitude estimation was employed than magnitude production. The authors concluded that magnitude estimation should be viewed with caution in the determination of the exponent due to the large scatter of results. However, despite the uncertainties magnitude estimation resulted in a mean value of the exponent of 0.93, which is similar to the mean exponent of 1.17 derived from magnitude production. Fothergill and Griffin (1977) also compared the methods of magnitude estimation and magnitude production and, contrary to the findings of Clarke and oborne (1975a), they found that magnitude production produced more variation in the value of the exponent than magnitude estimation. Magnitude estimation resulted in a mean value of the exponent of 1.12. Magnitude production resulted in a mean exponent of 1.64. At higher value of the exponent for magnitude production than magnitude estimation agrees with the findings of Clarke and Oborne (1975a). Leatherwood and Dempsey (1976a) also found large fluctuations between subjects in the value of the exponent. A mean exponent of 1.14 was determined for the evaluation of intensity and 1.24 for the evaluation of discomfort. Similar values of the exponent were determined by Hiramatsu and Griffin (1984). They conducted two experiments which resulted in mean exponents of 0.96 and 1.20.

Shoenberger and Harris (1971) investigated the frequency dependence of the exponent in the power law describing the effect of magnitude. The exponent varied between 0.86 and 1.04 for frequencies in the range 3.5 to 20 Hz. The evidence for the frequency dependence of the exponent was unconvincing. Miwa (1968a) and Jones and Saunders (1974) also found that the effect of frequency on the value of the exponent was not significant.

The studies reviewed show that the effect of magnitude on the subjective reaction to whole-body vibration can be reasonably accurately described by a power function of the form $\psi = k\varphi^n$. There is little evidence that the relation is frequency dependent, however, there were large fluctuations in the value of the exponent between individuals and experimental techniques. Considering the variability of the value of the exponent, it may be concluded that the effect of magnitude can be described by an average growth function. The studies resulted in values of the exponent of about unity, so it seems reasonably accurate to describe the relation between the subjective magnitude, ψ, and the objective magnitude, φ, as $\psi = k\varphi$. Most of the studies reviewed involved stimuli at magnitudes substantially greater than magnitudes which may be experienced in buildings during the passage of nearby trains. Only one study (Miwa, 1968a) involved magnitudes less than 0.1 ms^{-2} r.m.s. To quantify vibration from passing trains with respect to annoyance, further work is necessary to investigate the effect of vibration magnitude at acceleration magnitudes near the perception threshold.

2.3 A REVIEW OF INVESTIGATIONS OF THE TIME DEPENDENCY OF SUBJECTIVE REACTION TO WHOLE-BODY VIBRATION

2.3.1 Introduction

Time dependency is one factor that must be considered in the assessment of subjective reaction to building vibration. Although laboratory and field studies have been conducted to investigate the time dependency, as yet, there is no concensus of opinion on the effect of exposure duration.

According to von Gierke (1975), the International Standard ISO 2631 (1974) proposes a time dependency supported by results from studies by Miwa et al (1973) and Simic (1970). The standard provides a guide to the acceptability of whole-body vibration for stimuli of duration 1 minute to 24 hours. Between 10 minutes and 8 hours, this corresponds approximately to root-mean-square averaging which implies a time dependency given by (acceleration magnitude)^2 x time = constant. The allowable magnitudes proposed change very little between 1 minute and 10 minutes. The standard does not provide a time dependency for motions of less than 1 minute, however, if horizontal extrapolation were assumed, the resulting time dependency is very different than that implied by the commonly used root-mean-square procedure. Figure 2.3.1 is adapted from Griffin (1982) and shows the exposure limit defined in ISO 2631 (1974) for exposure durations from 1 minute to 24 hours. The ISO time dependency is compared with various time dependencies given by $a^n t$ = constant, where a is the acceleration magnitude, t is the duration of exposure and n = 1, 2, 3, 4 and ∞.

Griffin and Whitham (1980a, 1980b) suggested that ISO 2631 (1974) overestimates the effect of duration. The time dependency implied by the results of their study led to the evolution of the vibration dose value (VDV ($ms^{-1.75}$) = $(\int_0^T a^4(t)\,dt)^{1/4}$ where a(t) is the frequency-weighted acceleration time history in ms^{-2}) (Griffin, 1984). The British Standard, BSI 6841 (1987), "Guide to the measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock," proposes a method of vibration evaluation involving the vibration dose value. This method is based on a 10:1 change of vibration magnitude being associated with a 10000:1 change in duration, i.e. (acceleration magnitude)^4 x time = constant.

In a recent review of research concerning duration effects of whole-body vibration on comfort, performance and physiological and biomechanical reaction, Kjellberg and Wikstrom (1985a) concluded that there is only weak evidence for the existence of an increasing effect as a function of exposure time. This supports the conclusion of an earlier review by Clarke (1979).

Several experimental techniques have been used to investigate the effect of duration of whole-body vibration on subjective response. This review categorises studies according to the technique employed: semantic scaling, magnitude estimation, matching methods, predictive methods, scaling methods and perception.

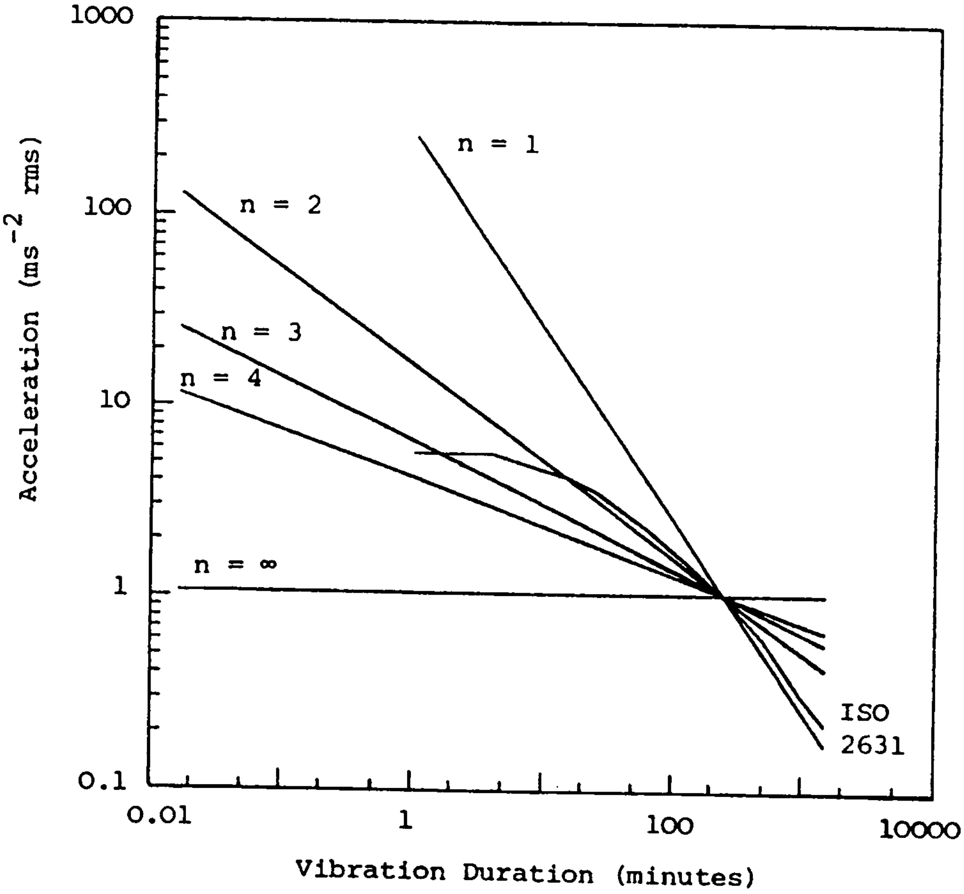

Figure 2.3.1 ISO 2631 (1974) time dependency compared with time dependencies given by $(\text{acceleration})^n \times \text{time} = \text{constant}$ where n = 1, 2, 3, 4 and ∞. Adapted from Griffin (1982).

2.3.2 Semantic Scaling

The method of semantic scaling involves providing the subject with a choice of graded adjectives which may be used to describe, for example, the degree of discomfort or unpleasantness produced by the stimuli. The method may appear useful but it is limited because the scale is only ordinal so that the relationship between labels on the same scale cannot be quantified. The interpretation of the adjectives used for the semantic labels may vary between subjects and it is difficult to compare results from different studies unless the same semantic labels are used.

2.3.2.1 Clarke and Oborne (1975b)

Surveys on trains and hovercrafts were carried out by Clarke and Oborne (1975b) together with vibration measurements to investigate the reaction of passengers to public service vehicle ride. The passengers rated the discomfort using a semantic scale and specified the time at which the judgement was made. The duration of exposure for the single judgement from each passenger was determined by subtracting the journey start-time from the time at which the judgement was made. The exposure time varied from 0 to 20 minutes for the hovercraft trip and from 0 to 150 minutes for the train ride. Correlation of duration with subjective judgement showed no change in discomfort over exposure time. Each subject contributed to only one data point, therefore it may have been necessary to determine whether the subjective magnitude corresponding to one subject's response was equal to the subjective magnitude corresponding to the same response from another subject. However, there was no such quantitative interpretation of individual subjective judgement. A very simple estimate of vertical motion was made for the time segments of each journey in which the majority of passengers made their judgements. An effect of changes in acceleration magnitude and frequency over the duration of the journey may have masked any duration effects, however, this is not possible to ascertain since detailed analysis of the motion was not made.

2.3.2.2 Miwa, Yonekawa and Kojima-Sudo (1973)

Miwa et al (1973) exposed ten subjects in the laboratory to z-axis and x-axis whole-body, broad band random vibration for 2 to 4 hours. The subjects were asked to respond every 30 minutes using a 5-label semantic scale ranging from "insensible (1)" to "unbearable (5)", after which the threshold of perception was measured. The 3-hour session was stopped every 15 minutes and the subject matched 10 Hz sinusoidal motion with the vibration session as a whole. The 4-hour session was presented without rest, the 2 and 3-hour sessions with a 10 minute rest every 30 minutes. The semantic ratings increased slightly over the exposure time. The increase was 0.5 on the 5-point scale, which is a small change over such long exposures. Miwa et al concluded that the equivalent magnitudes resulting from the subjective matching increased by about 3 dB over a

3-hour exposure. Figure 2.3.2 is adapted from Miwa et al (1973) and shows the subjective rating as a function of exposure duration for the 3-hour session. This corresponds to a time dependency given by (acceleration magnitude)$^{7.2}$ x time = constant. Miwa et al compared their results with the fatigue decreased proficiency boundary of a Draft International Standard, DIS 2631 (1972), in a figure which shows three data points corresponding to their results. The figure suggests support for the time dependency of the Draft International Standard. However, the three points are not taken directly from the experimental data but are a surprising interpretation of the results which was based largely on "critical times". A turning point of one to three hours, after which the rating does not increase, was suggested as present for each session, however, the results did not show convincing evidence for such a "critical time".

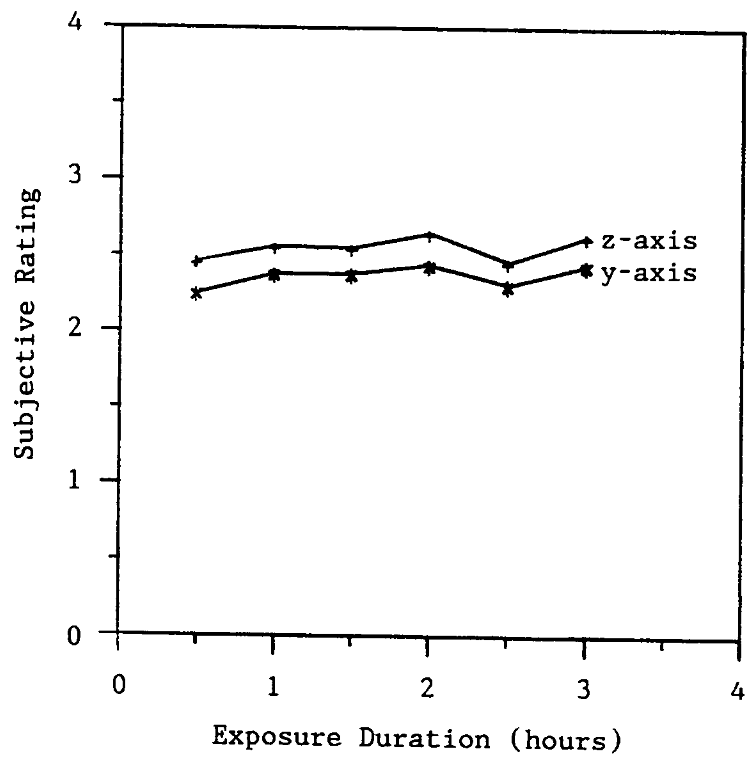

Figure 2.3.2 Subjective ratings as a function of exposure duration for the 3-hour session. Adapted from Miwa et al (1973).

2.3.3 Magnitude Estimation

The method of magnitude estimation involves the use of a reference stimulus which is assigned an arbitrary number corresponding to the subjective magnitude. Test stimuli are presented to the subject after the reference stimulus. The subject is asked to assign a number to each stimulus corresponding to the subjective magnitude as a multiple of the reference stimulus. This method has several advantages over semantic scaling. With the semantic method the scale is only ordinal as the relationship between semantic labels is unknown. If it is assumed that a linear and continuous scale is obtained from magnitude estimation, the ratio scale which results is far more useful than an ordinal scale since the quantitative relationship between responses can be determined. In a study by Fothergill and Griffin (1977) semantic and numerical methods were compared. They showed that the variability between subjects as reflected by $\sigma/\bar{x}$ (where σ is the standard derivation and $\bar{x}$ the mean response) was significantly less for numerical methods than for semantic methods. This provides further support of the use of magnitude estimation in preference to semantic scaling.

2.3.3.1 Clevenson, Dempsey and Leatherwood (1978)

Clevenson et al (1978) employed the method of magnitude estimation to investigate the effect of duration. The experiment took place in an aircraft simulator. Subjects were presented with a reference stimulus of 9 Hz vertical sinusoidal vibration at 0.1 g r.m.s. for 10 seconds. The test stimuli consisted of random vertical vibration with a 10 Hz bandwidth centred at 5 Hz. Each subject received test stimuli for one of nine durations (0.25 to 60 minutes) at one of four magnitudes. The number of presentations of the reference stimulus varied with the duration of the stimuli received. Averaging over all subjects and durations, a linear relationship between magnitude estimate and acceleration magnitude was obtained. The effect of exposure duration on the magnitude estimate was presented and showed a significant decrease in magnitude estimate with increasing duration at all magnitudes above the threshold of perception. A major problem in this study was that if the exposure time did affect discomfort then it seems likely that the reference stimulus was similarly affected and therefore the discomfort produced by the reference stimulus was not constant over the duration of the experiment. Another likely source of error was that the number of presentations of each stimulus was not balanced, for example, a stimulus of 0.025 g for 60 minutes was presented once to each of 12 subjects but a stimulus of 0.025 g was presented for 0.25 minutes, 36 times to each of 18 subjects.

2.3.3.2 Hiramatsu and Griffin (1984)

Hiramatsu and Griffin (1984) sought to determine the exponents of psychophysical power functions for the effect of both magnitude and duration of vibration. They exposed subjects to 8 Hz vertical vibration at five magnitudes and with five durations varying from 2 to 50 seconds. Multiple regression analysis was employed to relate the geometric mean of magnitude estimates, ψ, the r.m.s. acceleration (ms^{-2}), a, and the duration (s), t. Figure 2.3.3 is adapted from Hiramatsu and Griffin and shows the effect of duration on the magnitude estimate for each acceleration magnitude. The power function resulting from the multiple regression was given by $\psi = ka^{0.964}\ t^{0.563}$ from which the trade-off between magnitude and duration was given by $k = a^{1.7}t$. This result implies an even greater effect of duration of vibration on discomfort than that corresponding to the r.m.s. procedure ($k = a^2t$) for time dependency and does not support the findings of Griffin and Whitham (1980a, 1980b) who suggested the r.m.s. procedure overestimated the effect of duration. Hiramatsu and Griffin (1984) suggested the anomaly may be explained by the findings of Hiramatsu et al (1977) that magnitude estimation produces a larger effect of duration than the method of adjustment employed by Griffin and Whitham (1980a).

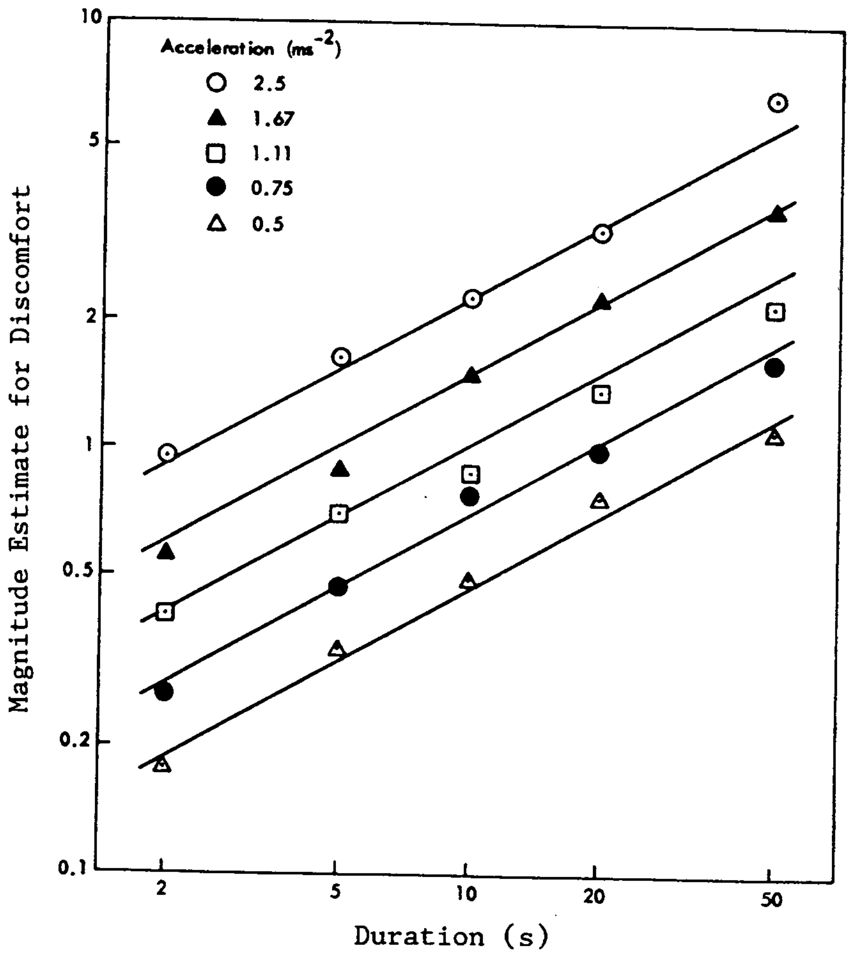

Figure 2.3.3 Magnitude estimates for durations at five acceleration magnitudes. Adapted from Hiramatsu and Griffin (1984).

2.3.4 Matching Methods

Matching methods require either the subject or the experimenter to adjust a stimulus to the magnitude at which the subject considers it to produce a sensation having a specified relation to another stimulus. Matching methods have been shown to produce results with less scatter than results obtained by semantic methods (see Fothergill and Griffin, 1977) but the subject is presented with a more difficult and possibly less realistic task.

2.3.4.1 Griffin and Whitham (1976)

Griffin and Whitham (1976) conducted an experiment using the method of magnitude production to determine whether the relative discomfort produced by two stimuli of different frequencies depended on the duration of the vibration exposure. By means of a potentiometer control, subjects matched 10–second periods of 4 Hz vertical motion to 16 Hz vertical motion at 0.75 ms^{-2} r.m.s. in one session and matched 16 Hz motion to 4 Hz motion at 0.75 ms^{-2} r.m.s. in another session. The two stimuli were alternated continuously for a total duration of 36 minutes. A reading of the magnitude of the matched stimulus was taken after every four alternations, after which the gain of the potentiometer control was changed. There was no significant interaction between frequency and duration and no significant effect of either frequency or duration. Thus, it was concluded that any duration effect would be the same for the two stimuli and so the shape of frequency weightings employed to assess vibration stimuli need not be a function of the exposure duration.

2.3.4.2 Kjellberg and Wikstrom (1985b)

Kjellberg and Wikstrom (1985b) employed the method of magnitude production in three experiments to investigate the effect of duration on discomfort. The first two experiments involved reference motions at 2.3 and 1.1 ms^{-2} r.m.s. The frequency of the reference and test motions was 31.5 Hz. The first experiment was conducted to investigate durations between 0.1 and 4 seconds and resulted in growth functions of 0.25 for the equivalence to 1.1 ms^{-2} r.m.s. (i.e. $a^4t = k$) and 0.21 for the equivalence to 2.3 ms^{-2} r.m.s. (i.e. $a^{4.8}t = k$). The second experiment was conducted to investigate durations between 1 and 128 seconds. The results showed a critical time for both reference magnitudes at 3 seconds. The growth rate was 0.18 and 0.13 for durations of less than 3 seconds and 0.03

and 0.06 for durations greater than 3 seconds, for the equivalence to 1.1 and 2.3 ms^{-2} r.m.s. respectively. The third experiment involved presentation to subjects of stimuli of frequencies of 6.3 and 31.5 Hz and durations between 0.19 and 117 seconds. In one session, a 6.3 Hz reference motion at 1.1 ms^{-2} r.m.s. was matched to a 6.3 Hz test motion. In another session, a 31.5 Hz reference motion at 2.3 ms^{-2} r.m.s. was matched to a 31.5 Hz test motion. The results showed no critical time for 6.3 Hz and a growth rate of 0.1 ($a^{10}t = k$). For 31.5 Hz there was a critical time at 4 seconds. The growth rate was 0.14 for durations between 0.2 and 3 seconds ($a^7t = k$) and 0.04 for durations between 3 and 117 seconds ($a^{25}t = k$).

Figure 2.3.4 is adapted from Kjellberg and Wikstrom (1985b) and illustrates the results of the third experiment. Kjellberg and Wikstrom suggested that a critical time may exist at higher frequencies (31.5 Hz) but not at low frequencies (6.3 Hz). Kjellberg and Wikstrom suggested that the absence of a critical time at low frequencies explains why Griffin and Whitham (1976) found no evidence of a critical time, since their study involved stimuli at 8 Hz only. However, Griffin and Whitham (1980a) carried out a further study on the effect of pulse duration with various frequencies and durations, including 32 Hz for 16 seconds, and they found little evidence of a change in slope with duration.

The three experiments conducted by Kjellberg and Wikstrom resulted in growth functions of well below 0.5 which suggests the time dependency implied by the r.m.s. procedure ($a^2t = k$) overestimates the duration effect. However, the results suggest that even the r.m.q. and vibration dose value procedures ($a^4t = k$) may overestimate the influence of exposure duration. The low growth functions could be attributed to the subjects being asked to base their matching "on the effect at the end of the pulse". This may have reduced the magnitude of the matched stimulus since the subject may not have considered the pulse as a whole. The reduction is likely to have been greater for stimuli of long duration than short duration. This would have resulted in a reduction in the growth function.

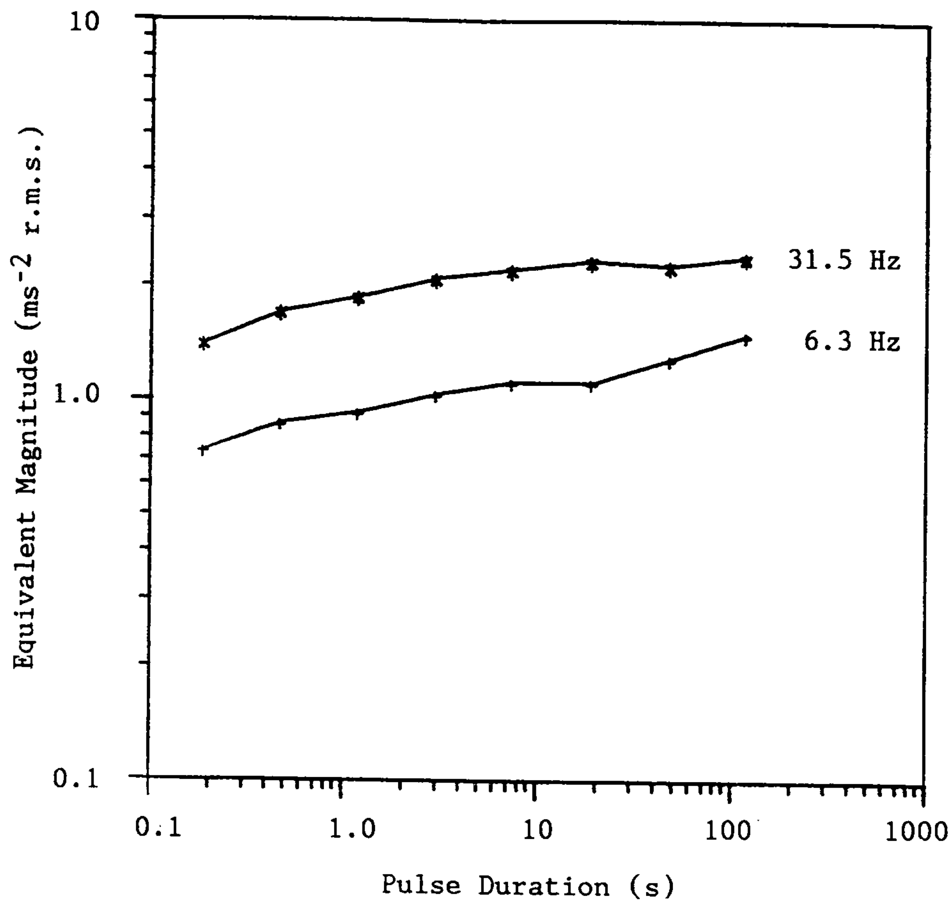

Figure 2.3.4 Equivalent magnitude as a function of pulse duration. For 31.5 Hz the ordinate is the magnitude equivalent to 31.5 Hz at 2.3 ms^{-2} r.m.s. For 6.3 Hz the ordinate is the magnitude equivalent to 6.3 Hz at 1.1 ms^{-2} r.m.s. Adapted from Kjellberg and Wikstrom (1985b).

2.3.4.3 *Kjellberg, Wikstrom and Dimberg (1985)*

The method of cross-modality matching was employed by Kjellberg, Wikstrom and Dimberg (1985) to determine the effect of duration for stimuli up to 64 minutes in duration. Subjects matched a reference broad band noise stimulus to simultaneously presented random vertical vibration with most energy at either 3.1 Hz or 6.3 Hz. This method has some advantages over matching between two vibration stimuli. Subjective matching can be conducted during vibration exposure which saves time and avoids the effect of interruptions in the vibration exposure. The equivalence between noise and vibration was determined in the first session in which subjects matched the noise stimulus with vibration presented simultaneously for 6 seconds at four magnitudes. In the second session, subjects were exposed to vibration for 64 minutes. During the exposure, cross-modality matching was conducted at 14 intervals between 0.25 minutes and 64 minutes. The equivalence between noise and vibration determined from the first session was employed to transform the noise settings of the second session to equivalent acceleration magnitudes. This resulted in a growth rate between equivalent magnitude and duration of 0.04 for the 3.1 Hz vibration stimulus and of 0.045 for the vibration at 6.3 Hz. The results are shown in Figure 2.3.5 which is adapted from Kjellberg et al (1985). The rate of increase in equivalent magnitude with time is much smaller than suggested by other studies e.g. Kjellberg and Wikstrom (1985b), Griffin and Whitham (1980a, 1980b), Miwa (1968b), however, the individual results show that the growth rate varied greatly within and between subjects and Kjellberg et al suggested that the variability reflects the difficulty of the task rather than real differences. The important aspect of this study is the indication that the effect of duration is constant up to 64 minutes.

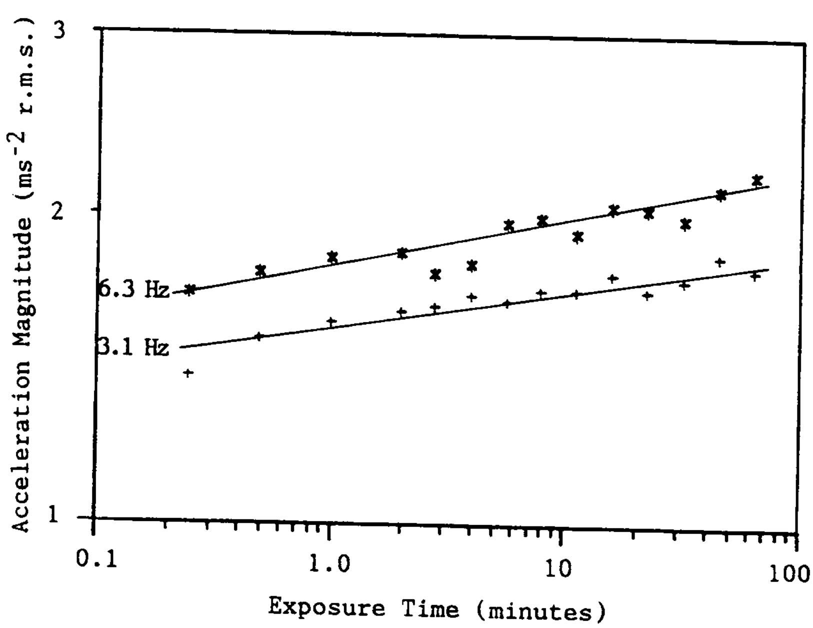

Figure 2.3.5 The effect of exposure duration on discomfort for 3.1 Hz and 6.3 Hz vibration. Mean sound settings (transformed into vibration magnitudes) as a function of exposure time. Adapted from Kjellberg et al (1985).

2.3.4.4 Miwa (1968b)

Miwa (1968b) investigated the effect of vibration duration of pulsed sinusoidal motion. Subjects matched a continuous sinusoidal motion of 3 seconds duration with pulsed sinusoidal motion of fixed magnitude and of durations varying from 0.007 to 6 seconds. The nominal frequencies of the pulse and the continuous motion were the same. Frequencies from 2 Hz to 200 Hz were investigated.

Linear regression analysis of the mean equivalent magnitudes of continuous sinusoidal motion as a function of the pulse duration on log–log coordinates resulted in an average gradient of 7 dB/decade of duration, i.e. a growth rate of 0.35 ($k = a^{2.9}t$). Miwa (1968b) suggested that the results of his study show a critical time at 2 seconds for frequencies between 2 and 60 Hz and at 0.8 seconds for frequencies between 60 and 200 Hz. However, very few data points in the figures show support for such a critical time.

2.3.4.5 *Griffin and Whitham (1977, 1980a,b)*

Griffin and Whitham (1977, 1980a,b) conducted experiments using the method of constant stimuli to investigate the effects of "pulse" duration on human discomfort produced by vertical vibration. The first two experiments involved the alternate presentation of a reference stimulus of 10 Hz motion at 1 ms^{-2} for 1 second followed by a test stimulus. The subjects indicated whether the reference or test motion was more uncomfortable. The first experiment was conducted to investigate durations up to 4 seconds. Sixty–four test stimuli consisting of all combinations of eight durations and eight magnitudes were presented. The experiment was conducted in four parts associated with four test frequencies of 4, 8, 16 and 32 Hz. The second experiment was conducted to investigate durations up to 32 seconds. Subjects were presented with 36 stimuli at 8 Hz consisting of all combinations of six durations and six magnitudes.

The 10th, 50th and 90th percentiles of the magnitude of vibration equivalent to the reference motion were shown as a function of duration on log–log coordinates. The results are shown in Figure 2.3.6 which is adapted from Griffin and Whitham (1980a). The first experiment resulted in regression lines with gradients of −0.29, −0.35, −0.41 and −0.45 for 4, 8, 16 and 32 Hz respectively. The second experiment yielded gradients of −0.4 when the reference motion was presented first and −0.35 when the test motion was presented first.

A third experiment was conducted to investigate whether motions with the same r.m.s. values but with different numbers of impulses resulted in the same equivalent magnitude. Five test motions consisted of 8 Hz 10–second motion with the same r.m.s. value but with between one and 16 evenly distributed impulses. The test motions were paired with eight magnitudes of 8 Hz 10–second reference motion. The results were presented as the equivalent magnitude as a function of the number of impulses. The results indicated that motions with fewer numbers of impulses at higher peak magnitudes caused more discomfort than motions with more impulses at lower magnitudes, even though they had the same r.m.s. magnitude. The growth function approximately corresponded to $k = a^4t$ when the reference motion was presented first and to $k = a^3t$ when the test motion was presented first. The results of the three experiments indicate that the time dependency implied by $a^2t = k$ overestimates the effect of the duration of vibration exposure on discomfort.

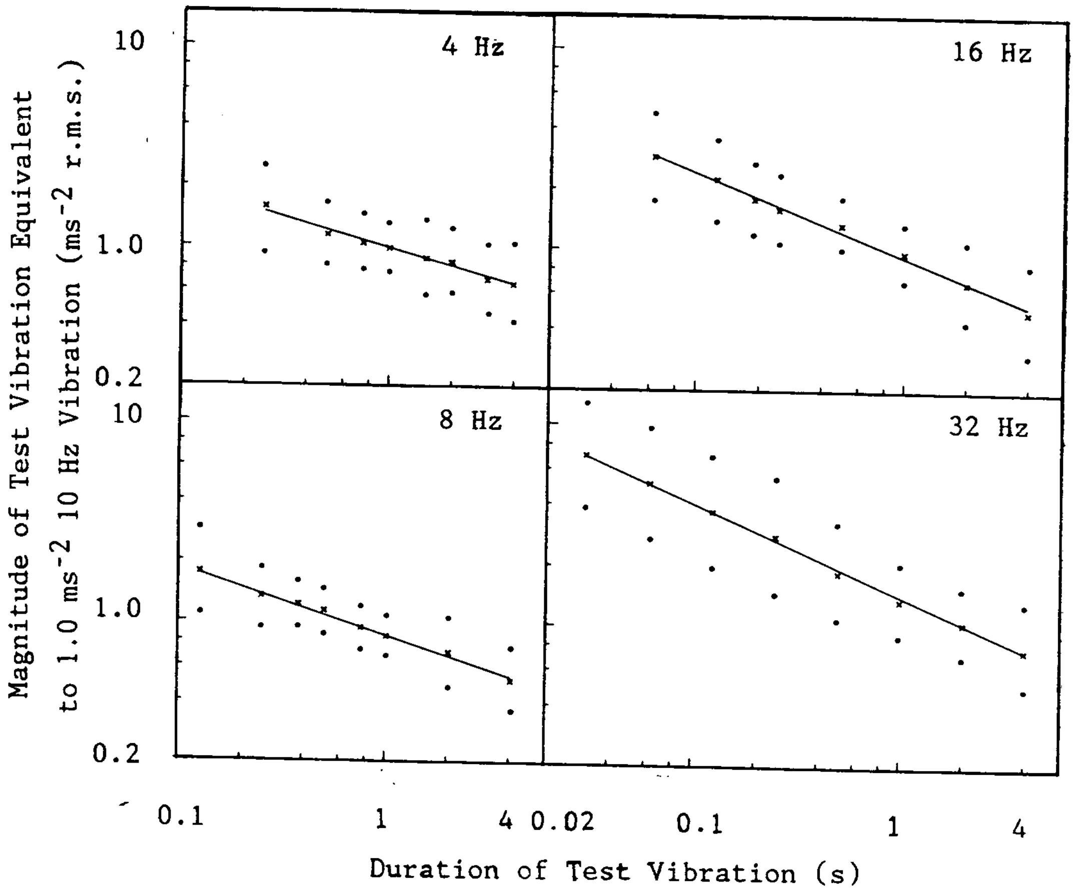

Figure 2.3.6 Effect of vibration duration on discomfort (x medians, . 10th and 90th percentiles). Adapted from Griffin and Whitham (1980a).

The results from the first experiment suggested that the rate of increase in discomfort with duration depended on the vibration frequency. The magnitudes of 16–second exposures at 4 and 32 Hz equivalent to 10 Hz reference motion can be predicted from the regression equations determined in the first experiment. By comparison of the equivalent magnitudes predicted for 16–second exposures with the equivalent magnitudes determined for one–second exposures at 4 Hz and 32 Hz, it appeared that for one–second exposures there was greater sensitivity to 4 Hz while for 32–second exposures there was greater sensitivity to 32 Hz. This unlikely result was tested in a fourth experiment in which subjects were presented with eight magnitudes of 32 Hz vibration paired with a fixed magnitude of 4 Hz vibration. The subjects attended three sessions corresponding to three durations of 1, 4 and 16 seconds. The durations of the reference and the test motions within each session were the same. The results showed little change in equivalent magnitude with exposure duration which indicates that the growth function does not depend on the frequency of vibration. This supports the findings of Griffin and Whitham (1976) in a study which concluded that the equivalence between 4 and 16 Hz vibration does not change over durations between 1 and 36 minutes. An attempt was made to explain the discrepancy between the results of the third and fourth experiments in terms of a possible frequency dependence of the growth in discomfort with acceleration magnitude. The explanation was tentative and inconclusive, however, the important aspect of the results of this study was the evidence that the time dependency implied by $a^2t = k$ overestimates the effect of the duration of vibration exposure on discomfort. The authors proposed that $a^4t = k$ is likely to describe more accurately the time dependency of discomfort produced by whole-body vibration.

2.3.5 Predictive Methods

Magid, Coermann and Ziegenruecker (1960), Simic (1970) and Oborne and Clarke (1974) used predictive methods to investigate the time dependency of discomfort produced by whole-body vibration. In this method the subjects were instructed to predict how long they would endure being exposed to a particular stimulus. The advantage of this method is that it is not necessary to expose the subjects to vibration for the durations under investigation. However, there is no evidence for the validity of the judgements - it is highly probable that subjects will respond with increasing acceptable durations when exposed to decreasing magnitudes of vibration, even though they might have no experience on which to base such a judgement.

2.3.5.1 Magid, Coermann and Ziegenruecker (1960)

Magid, Coermann and Ziegenruecker (1960) attempted to determine human tolerance to sinusoidal whole-body vibration for frequencies between 1 Hz and 20 Hz. Subjects were exposed to single frequency motion of gradually increasing amplitude. For "short-time" exposure durations, the subjects were asked to indicate when the motion had reached the amplitude corresponding to the tolerance limit. To determine one and three minute tolerance limits, a subject was asked to estimate approximately how much more acceleration they could have withstood for the exposure time specified. The results were shown as the limit corresponding to each exposure time as a function of frequency. The exposure limit decreased as the duration increased. However, this does not necessarily show that a time dependency exists as the subjects may not have based their judgements on previous experience.

2.3.5.2 *Simic (1970)*

Simic (1970) presented subjects with vertical sinusoidal whole-body motion with frequencies between 0.3 and 50 Hz. The subjects adjusted the amplitude of each stimulus to the magnitude which they predicted they could endure for one of four durations of exposure: 10 minutes, 1 hour, 2 hours or 4 hours. The "trade-off" between acceleration magnitude and time was shown. However, few points in the figure were based on the experimental data. Most points were based on an interpretation of the mean values of acceleration adjusted to correspond to the four durations. The mean acceleration corresponding to 1 hour duration was determined from the results from 10 subjects, but for 10 minutes and 2 hours the mean acceleration was based on results from only two and three subjects respectively. Fourteen frequencies in the range 0.7 Hz to 50 Hz were presented to determine acceleration magnitudes corresponding to 1 hour and 4 hours but only three frequencies were presented to determine magnitudes corresponding to 10 minutes exposure duration. The time dependency implied by the results of this study is likely to have been affected by inter-subject variability due to the imbalance of the numbers of subjects contributing to each data point. This study does not appear to be a sufficient basis on which to consider the time dependency of discomfort from whole-body vibration and yet, according to von Gierke (1975), the ISO 2631 time dependency is supported by this study by Simic.

2.3.5.3 *Oborne and Clarke (1974)*

Oborne and Clarke (1974) also used a predictive method to define semantic labels in terms of how long a subject would be prepared to withstand the vibration. Subjects were exposed to vibration at frequencies between 3 Hz and 80 Hz and employed semantic labels to rate the stimuli which were defined in terms of time. For example, "just comfortable" was defined: "As a passenger in public transport, I would not be willing to put up with this level of vibration for more than half an hour". The resulting equal comfort contours compared reasonably well with ISO $^1/_2$-hour and $1^1/_2$-hour reduced comfort boundaries. However, this does not necessarily validate the time dependency implied by the standard. The ratings were more likely to reflect the subjective magnitude of the stimuli than the effect of duration.

2.3.6 Perception

2.3.6.1 Miwa, Yonekawa and Kojima-Sudo (1973)

Miwa et al (1973) investigated the effect of duration of vibration on discomfort, perception and on several physiological factors. The study, which is described more fully in Section 2.3.2, exposed subjects to z-axis and x-axis motion for 2 to 4 hours. The threshold of perception was measured every 30 minutes at one frequency by gradually increasing the vibration magnitude until subjects indicated that they could feel the vibration. The motion was then decreased until subjects indicated they could no longer feel the vibration. The mean threshold shift as a function of exposure time was shown for the 4-hour session only and is shown in Figure 2.3.7 which is adapted from Miwa et al (1973). There was some evidence of an increase in threshold shift with duration compared with a control curve, however, the difference was only of the order of 1 to 2 dB over the 4-hour period and no statistical analysis was made.

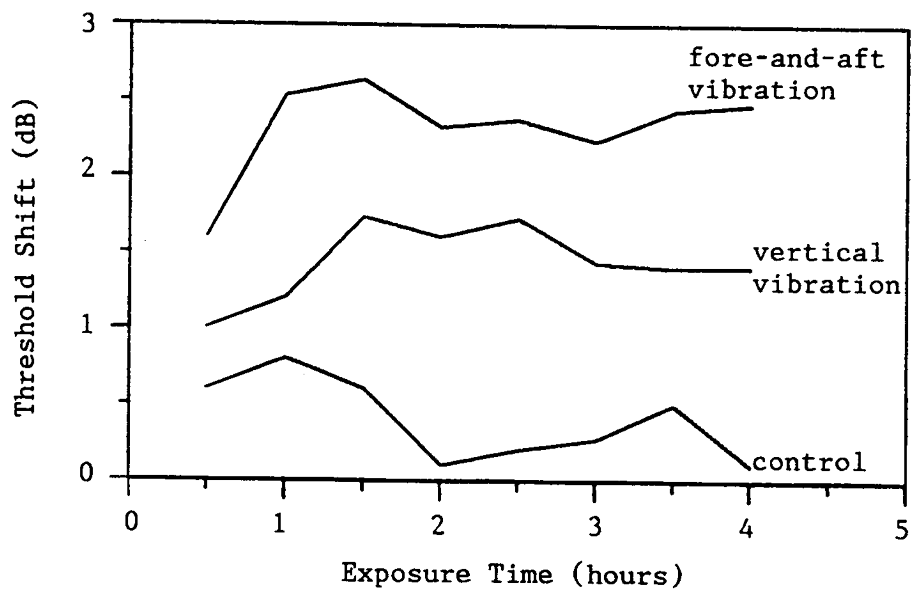

Figure 2.3.7 Mean threshold shift as a function of exposure duration for the 4-hour session. Fore-and-aft, vertical and control conditions. Adapted from Miwa et al (1973).

2.3.6.2 Parsons (1982)

Parsons (1982) investigated the effect of .the number of cycles of short duration vibration on vibration perception thresholds. The method of signal detection (Parsons, 1981) was employed to determine perception thresholds of 12 seated subjects to 16 Hz vertical vibration. The subjects were presented with between 1 and 64 cycles of motion during a 4-second period when a light was on and were asked to indicate whether they felt any vibration. Fisher's least significant difference test was applied between individual pairs of mean thresholds and showed thresholds for 1, 2 and 4 cycles of motion were significantly greater than for 8, 16, 32 and 64 cycles. The effect was small and the application of the results is limited as it was a small study involving few subjects and with only one frequency of motion.

2.3.6.3 Miwa, Yonekawa and Kanada (1984)

The threshold of perception of pulsed sinusoidal vibration as a function of pulse duration was investigated by Miwa, Yonekawa and Kanada (1984). Ten recumbent male subjects were presented with vertical (x-axis) and horizontal (y-axis and z-axis) pulses of sinusoidal motion in the frequency range 1 Hz to 100 Hz. The subjects judged whether they could feel the stimuli after two pulses of each stimulus separated by five-second intervals. Different pulse durations were presented at each frequency. The maximum pulse duration was four seconds and the number of durations presented at each frequency of vibration depended on the frequency.

The results showed that higher vibration acceleration was required for the perception of shorter pulses than longer pulses. The rate of increase in the threshold acceleration with a reduction in pulse duration was less than predicted from the energy law (10 dB/decade of duration), i.e. the exponent was greater than 2. On the basis of the results, Miwa et al proposed an integration time of 0.25 seconds, instead of 0.125 seconds recommended by the International Organization of Standardization.

2.3.7 Discussion and Conclusions

Building vibration induced by passing trains is intermittent and occurs at approximately regular intervals with up to about 400 trains passing in 24 hours. The duration of perceptible building vibration induced by each event ranges from about 2 seconds to 45 seconds, with most events lasting between 10 and 15 seconds (Woodroof and Griffin, 1987). Due to these characteristics railway-induced building vibration cannot be classified as either impulsive or continuous motion. Previous studies concerning the effect of exposure duration on subjective response to whole-body vibration have investigated response to continuous motion or single events but not to intermittent vibration. International Standard ISO 2631 (1978) suggests that the time dependency implied by root-mean-square averaging may not be appropriate to impulsive type motions with crest factors (ratio of maximum peak to r.m.s. value) greater than 6. The standard does not provide a means of evaluating motions with higher crest factors. It would be advantageous if a method of evaluating railway-induced building vibration, included a time dependency applicable to short as well as long durations. There is also the need to differentiate between, for example, two events per day and two events per hour.

The time dependency suggested by International Standard ISO 2631 (1974) was supported by studies by Simic (1970) and Miwa et al (1973) according to von Gierke (1975). However, this review has shown that the evidence for such a time dependency is unconvincing. A time dependency defined by an exponent of 2 relating acceleration magnitude, a, and duration, t, ($a^2t = k$) implies that to maintain the same degree of discomfort with a four fold increase in vibration duration, the vibration magnitude should be decreased by a factor of two. This time dependency approximately corresponds to that implied by ISO 2631 (1974) from 10 minutes to 8 hours. However, there is substantial evidence, from the studies reviewed, that a time dependency defined by an exponent of 2 overestimates the effect of duration on subjective response to whole-body vibration. This implies that the effect of short duration exposures would be underestimated and long duration exposures would be overestimated. The results of a study by Miwa (1968b) indicated an exponent of 2.9 for exposure durations from 0.007 to 6 seconds. Griffin and Whitham (1980a) investigated the effect of exposure durations up to 32 seconds. Their results suggest an exponent of between 2.2 and 4. They tentatively concluded that the time dependency implied by the r.m.q. procedure ($a^4t = k$) may be equally applicable to long duration exposures as well as short duration exposures. The time dependency of $a^4t = k$ indicates that to maintain the same degree of discomfort with a doubling of the vibration magnitude, the exposure duration should be decreased 16 fold.

The findings of Kjellberg and Wikstrom (1985b) indicate an exponent of between 4 and 7.7 for durations up to 3 seconds. Their results suggest that a "critical time" may exist for frequencies greater than 31.5 Hz. Several other studies have suggested the existence of a critical time. ISO 2631 (1974) indicates that the critical time for vibration perception decreases from 2 to 0.8 seconds over the frequency range from 2 to 90 Hz. This was based on an investigation by Miwa (1968b) in which it was suggested that the results indicated a critical time at 2 seconds for frequencies between 2 and 60 Hz and at 0.8 seconds for frequencies between 60 and 200 Hz. But the evidence for such a critical time is unconvincing. Miwa et al (1973) proposed the existence of a "turning point" at 1 to 3 hours after which time a further increase in the duration of exposure had little effect on discomfort. However, very few data points in the study support such a finding.

In view of the lack of substantial evidence for a change in the duration effect with time, it seems reasonable to propose that a single method quantifying the time dependency of subjective response to whole-body vibration for all exposure durations would be appropriate. Review of previous studies leads to the conclusion that the rate of increase in subjective reaction with duration of vibration is substantially less than 0.5, i.e. the exponent, n, relating acceleration magnitude, a, and duration, t, ($a^n t = k$) is greater than 2. However, further work is required to establish whether such a time dependency is applicable to the intermittent vibration induced in buildings by passing trains.

2.4 A REVIEW OF INVESTIGATIONS OF THE THRESHOLD OF PERCEPTION OF TRANSLATIONAL WHOLE-BODY VIBRATION

2.4.1 Introduction

Vibration in buildings caused by passing trains is generally at very low magnitudes and is often not perceptible. For a person to be annoyed by railway-induced building vibration, the motion must be perceived. Thus, the threshold of perception is the first factor to be considered in the determination of subjective reaction to vibration from railways.

The Draft Addendum ISO 2631 (1980), "Guide to the evaluation of human exposure to vibration and shock in buildings (1 Hz to 80 Hz)," suggests that the base curves provided by the standard, for vertical (z-axis) and horizontal (x-axis and y-axis) motion, are in the general range of the human perception threshold. This implies that the perception threshold exists at a frequency weighted acceleration magnitude of approximately 0.005 ms^{-2} r.m.s. for vertical motion and 0.0036 ms^{-2} r.m.s. for horizontal motion. The base curves have the same frequency dependence as the acceleration limits defining the "reduced comfort boundary", "fatigue-decreased proficiency boundary" and "exposure limits" which are provided by ISO 2631 (1978), "Guide for the evaluation of human response to whole-body vibration." However, ISO 2631 (1978) proposes that the threshold of perception of vertical and horizontal motion exists at frequency weighted acceleration magnitudes of approximately 0.01 ms^{-2} r.m.s. The British Standard 6841 (1987), "Guide to the measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock," also proposes that the frequency dependence of the threshold of perception is the same as the frequency dependence of the subjective reaction to whole-body vibration at all magnitudes of perceptible vibration. However, the weightings differ from those defined in the International Standard. The British Standard states that fifty percent of alert fit persons can just detect a frequency weighted vibration with a peak magnitude of approximately 0.015 ms^{-2} (0.0106 ms^{-2} r.m.s.).

Investigations of the perception thresholds of vertical and horizontal whole-body vibration have been reviewed by Hanes (1970) and Gundry (1978). Hanes found little agreement between the findings of the studies, however, other investigations have been conducted since the review. Gundry compared the thresholds determined in 18 studies. A large proportion of these studies were concerned with motion at frequencies less than 1 Hz, for example, Walsh (1964), von Bekesy

(1939) and Chen and Robertson (1972).

The studies discussed in this section were conducted to determine perception thresholds for vertical and horizontal motion. The studies are reviewed in chronological order. Figures 2.4.1 and 2.4.2 show the thresholds from the studies which involved sitting and standing subjects exposed to vertical and horizontal motion respectively. Figures 2.4.3 and 2.4.4 show the thresholds from studies which involved recumbent subjects exposed to vertical and horizontal motion respectively. The thresholds indicated in ISO 2631/DAD1 (1980) and BS 6841 (1987) are also shown.

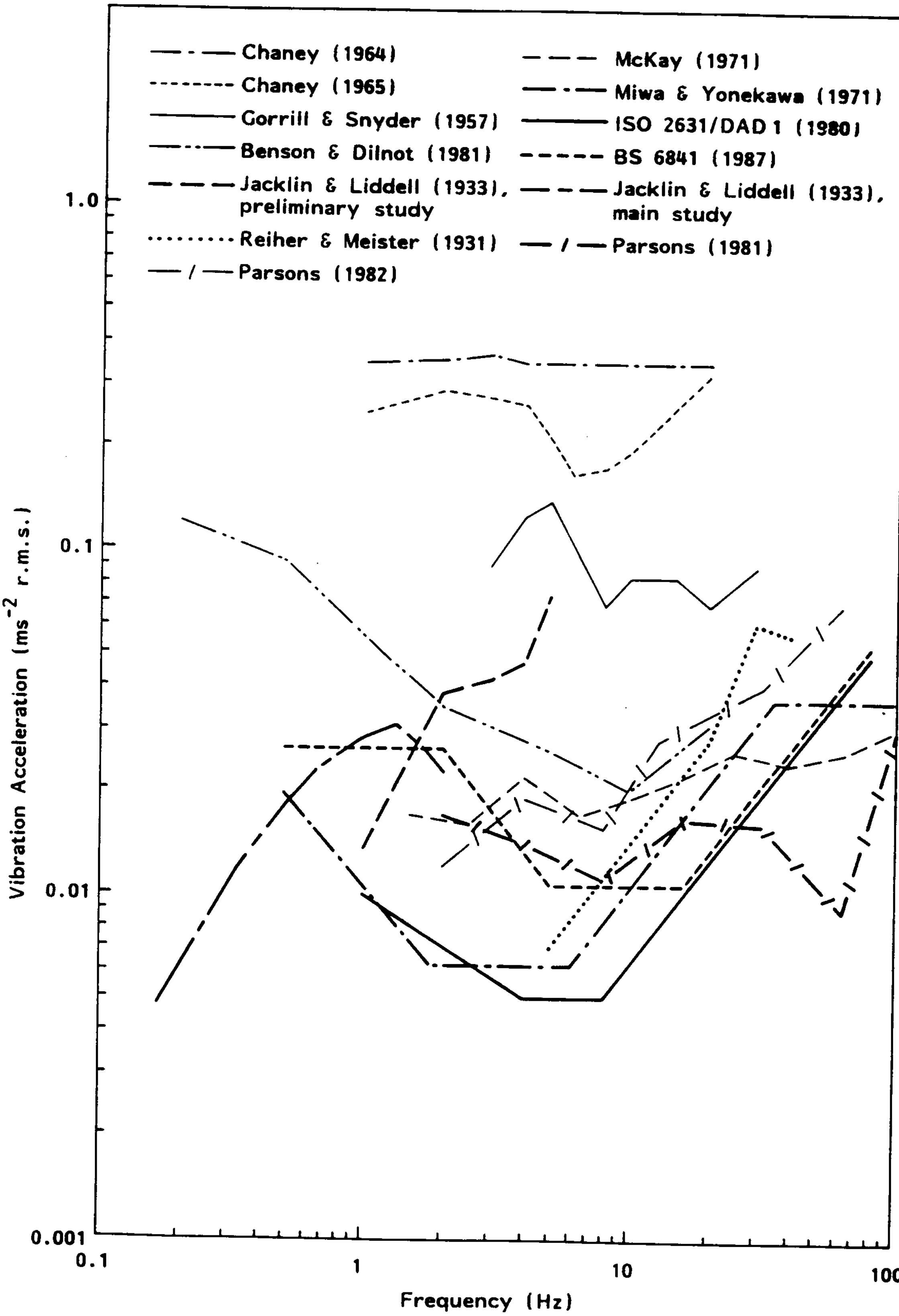

Figure 2.4.1 Perception thresholds of sitting and standing subjects exposed to vertical (z-axis) whole-body vibration.

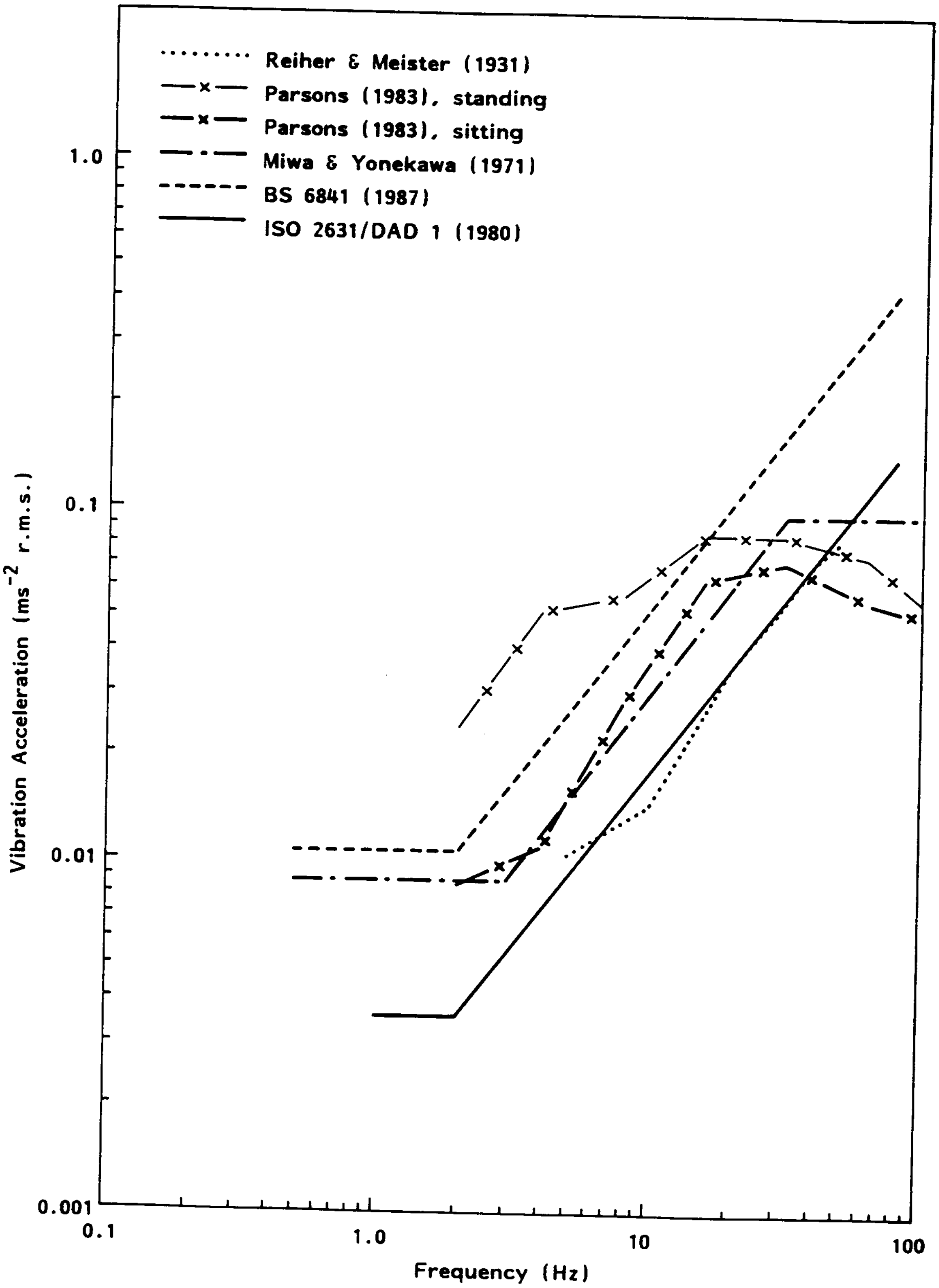

Figure 2.4.2 Perception thresholds of sitting and standing subjects exposed to horizontal (x–axis and y–axis) whole–body vibration.

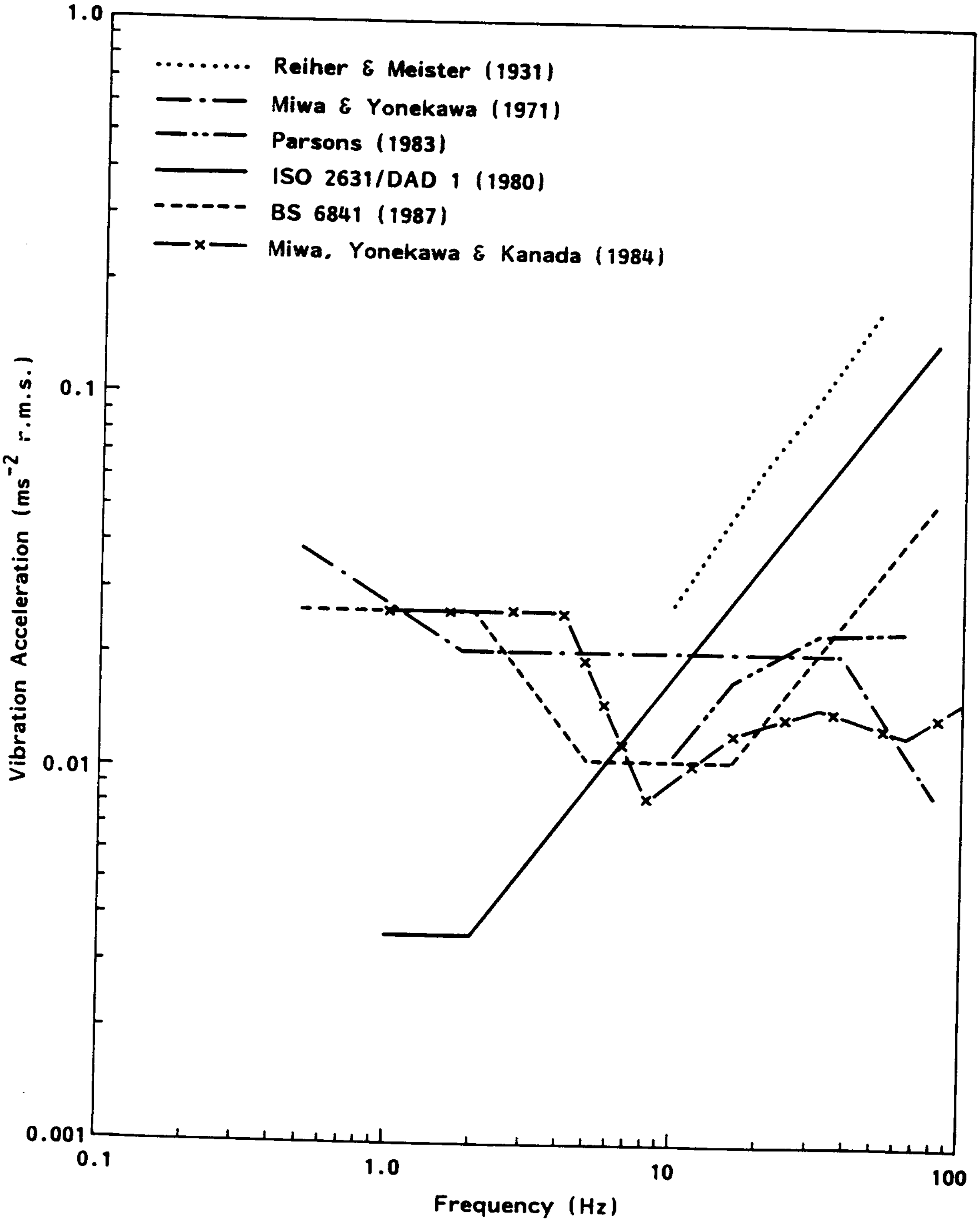

Figure 2.4.3 Perception thresholds of recumbent subjects exposed to vertical (x–axis) whole-body vibration.

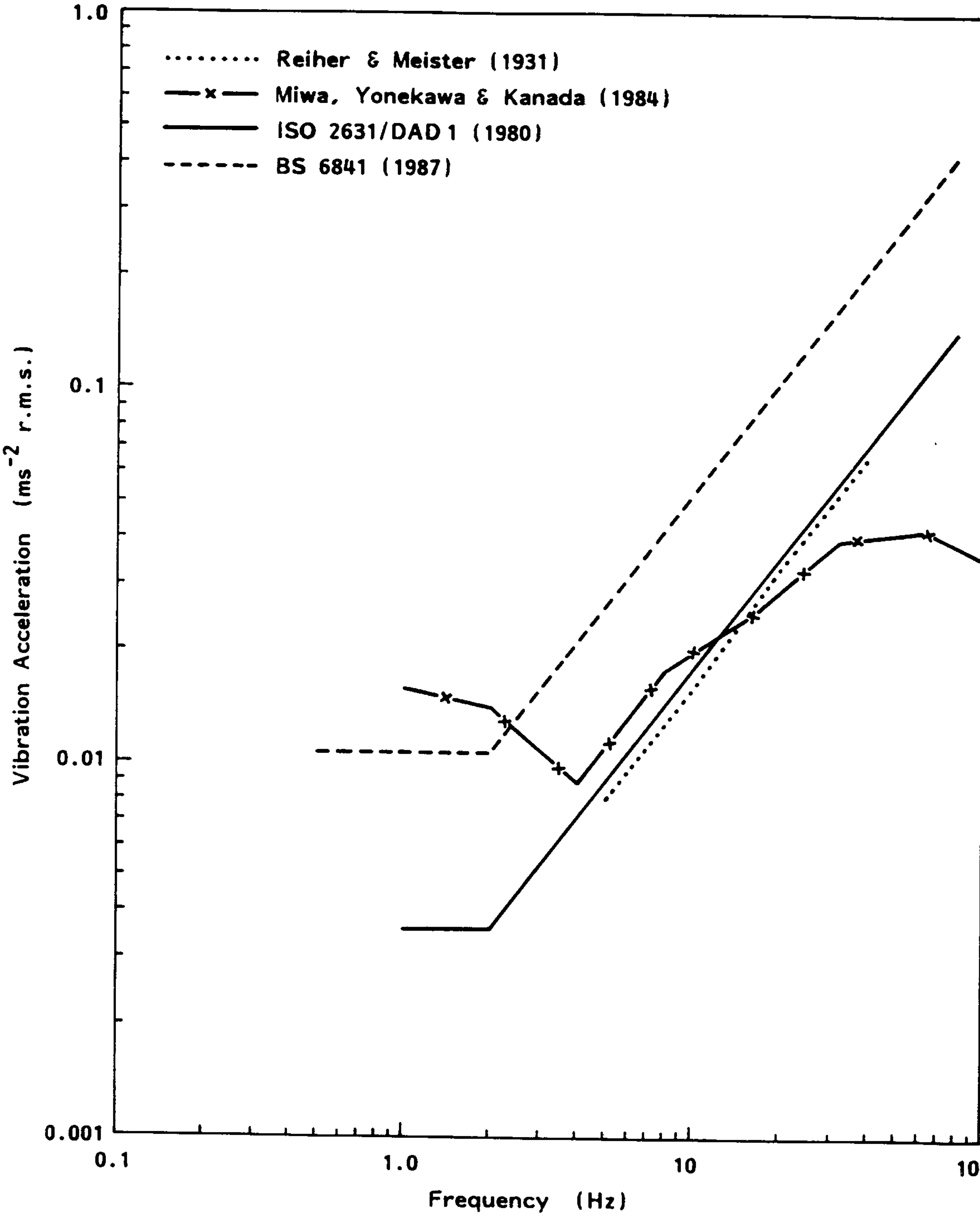

Figure 2.4.4 Perception thresholds of recumbent subjects exposed to horizontal (y-axis) whole-body vibration.

2.4.2.1 Reiher and Meister (1931)

An investigation was conducted by Reiher and Meister (1931) to determine perception thresholds for x-axis, y-axis and z-axis whole-body vibration of subjects in standing and recumbent postures. Ten subjects were exposed to sinusoidal vibration in the frequency range 3 Hz to 70 Hz, at amplitudes between 0.0001 cm to 1.0 cm. After five minutes of exposure to each stimulus, the subjects were instructed to rate the vibration using six semantic ratings: "not perceptible", "weakly perceptible", "easily perceptible", "strongly perceptible", "unpleasant" and "very unpleasant". Individual results were shown for standing and recumbent subjects exposed to vertical and horizontal motion separately, with the amplitude of motion as a function of frequency. The results were divided into sections by drawing boundary lines between the points corresponding to the various semantic ratings. Reiher and Meister (1931) proposed that the boundaries between the different domains could be described by the equation $an^k = c$, where a is the amplitude, n is the frequency, k is the exponent and c is a constant. The authors suggested that the value of the exponent is unity for the threshold of perception (i.e. the threshold is proportional to constant velocity). No details were reported of the method employed to determine the position of the boundary curves and the authors did not indicate the form of data analysis employed to find the equation of the boundaries. The lowest curve was indicated as corresponding to the perception threshold and was the boundary between the categories described as "not perceptible" and "weakly perceptible". Figures 2.4.1, 2.4.2, 2.4.3 and 2.4.4 show the perception thresholds determined by Reiher and Meister of standing subjects exposed to z–axis motion, standing subjects exposed to x–axis motion, recumbent subjects exposed to x–axis motion and recumbent subjects exposed to y–axis motion respectively. At frequencies greater than 8 Hz, the thresholds of standing and recumbent subjects indicated a similar frequency dependence to the thresholds proposed by ISO 2631/DAD1 (1980). Thresholds of standing and recumbent subjects exposed to vertical motion indicate greater sensitivity to acceleration than the International Standard. However, thresholds of standing and recumbent subjects exposed to horizontal motion were very similar to those proposed by ISO 2631.

2.4.2.2 Jacklin and Liddell (1933)

A large study was conducted by Jacklin and Liddell (1933) involving approximately one hundred seated men, to determine perception thresholds and comfort contours for vertical (z–axis), horizontal (x–axis and y–axis) and dual axis motion. Thresholds were determined of subjects exposed to vertical sinusoidal whole–body vibration in the frequency range 1 Hz to 5 Hz in a preliminary study and from 0.167 Hz to 2 Hz vertical motion and 0.167 Hz to 0.667 Hz horizontal motion in the main study. At each of seven magnitudes of motion the frequency was gradually increased. The subjects were instructed to indicate when each stimulus could be described by one of three semantic ratings: "perceptible", "annoying or disturbing" and "very uncomfortable, painful or unbearable". A histogram was continuously constructed for each amplitude selected to indicate the number of responses at each frequency corresponding to the three semantic ratings. The procedure was repeated with new subjects until the histogram showed that at least one half of the total readings fell within 20% above or below the final average value. Data points out of line were rechecked by taking readings from more subjects. The subjects were provided with a surprising definition of "perceptible" which included the effects of vibration on vision: "You now feel that you are moving or that distant objects are moving slightly or becoming hazy." Figure 2.4.1 shows the thresholds for vertical motion obtained in a preliminary study (1 Hz to 5 Hz) and in the main study (0.167 Hz to 2 Hz). The unusual experimental method, which involved repetition of the procedure until the required result was obtained, the "rechecking" of "out of line" points and the inclusion of the effect on vision in the definition of "perceptible" leads to the conclusion that it would be inadvisable to place much emphasis on these results.

2.4.2.3 Gorrill and Snyder (1957)

The method of semantic rating was employed by Gorrill and Snyder (1957) in a study in which they exposed five seated men to vertical sinusoidal whole-body vibration. The subjects were presented with seven stimuli in the frequency range 3 Hz to 30 Hz. The magnitude of each stimulus was gradually increased until the subject indicated the vibration corresponded to one of five semantic ratings describing perception, annoyance or tolerance. The first semantic rating, "threshold of perception", was defined: "By intense concentration and with prior knowledge that the vibration is going to appear, you first detect the presence of vibratory motion." The results indicated that minimum sensitivity was between 4 Hz and 6 Hz, whereas ISO 2631/DAD1 (1980) indicates that maximum sensitivity exists at these frequencies. The threshold was approximately a factor of ten greater than the ISO base curve and was greater than the thresholds from all other studies with the exception of Chaney (1964, 1965). The high threshold maybe a result of subjects performing a signal tracking task during the experiment.

2.4.2.4 Chaney (1964, 1965)

The threshold of perception of sitting subjects exposed to vertical motion was determined by Chaney (1964) for frequencies in the range 1 Hz to 27 Hz. The subjects sat on a hard, flat seat and were asked to adjust the magnitude of a sinusoidal test stimulus to correspond to each of four ratings: "perceptible", "mildly annoying", "extremely annoying" and "alarming". The criterion of perceptibility was defined: "This is the lowest intensity of vibration which can be felt." Equal comfort contours were determined for each semantic rating by plotting the median amplitude, velocity and acceleration as a function of frequency. The perception threshold was approximately constant at 0.35 ms^{-2} r.m.s. over the frequency range considered. The results of this study indicated much greater acceleration magnitudes corresponding to the threshold of perception than the results of other studies reviewed. The reasons for the high acceleration magnitudes for the perception threshold are not apparent.

A similar study was conducted by Chaney (1965) but subjects adopted a standing posture rather than a seated posture. The results from standing subjects were similar to those obtained from seated subjects. The perception thresholds from the two studies are shown in Figure 2.4.1. The threshold of seated subjects was constant over the frequency range considered, however, for standing subjects the threshold ranged from 0.16 to 0.34 ms^{-2} r.m.s. with maximum sensitivity at 6.5 Hz.

2.4.2.5 McKay (1971)

An experiment was conducted by McKay (1971) to determine the perception threshold of standing and sitting subjects exposed to vertical motion at 10 frequencies in the range 1.5 Hz to 100 Hz. Two criterion of perceptibility were compared: the lowest acceleration at which two out of three positive judgements were made, and the lowest acceleration at which one out of one positive judgements were made. At each frequency a series of discrete vibration stimuli was presented, increasing in magnitude from 0.001g peak (0.0069 ms^{-2} r.m.s.) in steps of 0.001g, until the duration of vibration was correctly indicated for at least two out of three or one out of one presentations. The difference between thresholds of male and female subjects was significant only at 6.5 and 15 Hz and between sitting and standing subjects at 1.5, 2.5 and 15 Hz. The difference between the results with the two criteria of perceptibility was significant at all frequencies except at 1.5 and 15 Hz. Since the distribution of results was positively skewed at high frequencies, the median perception threshold was examined. The threshold for combined results from both postures and from men and women (see Figure 2.4.1) remained at fairly constant acceleration over the frequency range considered, varying between 0.016 ms^{-2} r.m.s. at 2.5 Hz to 0.0305 ms^{-2} r.m.s. at 100 Hz. ISO 2631/DAD1 (1980) and BS 6841 (1987) (W_b frequency weighting) imply a greater frequency dependence of the perception threshold than this study.

2.4.2.6 *Miwa and Yonekawa (1971)*

Perception thresholds were determined of sitting, standing and recumbent subjects exposed to horizontal and vertical motion at frequencies between 0.5 Hz and 300 Hz in a study conducted by Miwa and Yonekawa (1971). Constant amplitude sinusoidal motion was presented to the subjects followed by a pause. After the pause, the stimulus was repeated at an acceleration magnitude increased by 0.1 dB. The stimuli were presented for three seconds for frequencies above 10 Hz and for six seconds for frequencies below 10 Hz. The results were presented in the form of contours fitted to the perception thresholds as a function of frequency. The contours were comprised of gradients corresponding to constant jerk, acceleration, velocity and displacement. The combined threshold of sitting and standing subjects exposed to vertical motion is shown in Figure 2.4.1 and can be seen to be similar to the threshold proposed in ISO 2631/DAD1 (1980). However, for horizontal motion the threshold of sitting and standing subjects was more similar to the threshold proposed in the British Standard (BS 6841, 1987) than ISO 2631/DAD1 (1980) except at frequencies above about 32 Hz. Recumbent subjects were exposed to vertical and horizontal motion, but it is not clear which axis of horizontal motion (z or y) was presented to the subjects. The frequency dependence of the vertical perception threshold of recumbent subjects (see Figure 2.4.3) was very different to the findings of other studies with recumbent subjects (e.g. Reiher and Meister (1931), Parsons (1983)) and also very different to the proposed thresholds of the International and British Standards. The threshold was at a constant acceleration of 0.021 ms^{-2} r.m.s. from 1.8 Hz to 38 Hz. The results indicated less sensitivity to acceleration below 1.8 Hz and greater sensitivity to acceleration at frequencies above 38 Hz than the standards.

2.4.2.7 *Benson and Dilnot (1981)*

The "double random staircase" method was employed in a study by Benson and Dilnot (1981) to determine the perception threshold of seated subjects exposed to vertical motion in the frequency range 0.2 Hz to 20 Hz. The stimuli consisted of two "staircases" of sinusoidal motion at the same frequency, with one staircase starting below threshold and the other above threshold and with random switching between the two. If the subjects indicated they could feel a stimulus, the next vibration of that staircase was presented at a reduced magnitude. If the stimulus was not detected, the next stimulus was presented at a greater magnitude. This procedure was repeated until the two staircases converged. The mean threshold acceleration as a function of frequency, on log–log coordinates showed an approximately monotonic fall in threshold with frequency from 0.2 Hz to 10 Hz and then an increase at 20 Hz (see Figure 2.4.1). The threshold was approximately five times greater than the ISO base curve, however, the shape of the threshold contour was similar to the frequency dependence of the International Standard (ISO 2631/DAD1 (1980)).

2.4.2.8 Parsons (1981, 1982, 1983)

Parsons (1981) employed the signal detection theory model (see Licklider, 1964) to provide a means of determining a subject's absolute perception threshold which is independent of the subject's inclination to report that a stimulus is present. Subjects were asked to indicate whether they could feel the vibration on occasions when vibration was present and on occasions when it was not present. The perception threshold was defined as the magnitude at which there were 75% hits and 25% false alarms. The threshold was determined of sitting and standing subjects exposed to vertical (z–axis) sinusoidal motion in the frequency range 2 Hz to 100 Hz. Except at 8 Hz, there was no significant difference between the perception thresholds of male and female subjects. At frequencies less than 8 Hz sitting subjects were more sensitive, while above 16 Hz subjects were more sensitive when standing. However, the difference between sitting and standing subjects was small compared with individual variations. The threshold of standing subjects is shown in Figure 2.4.1 and indicates greater sensitivity to acceleration at frequencies above 31.5 Hz and less sensitivity to acceleration below 31.5 Hz than suggested by ISO 2631/DAD1 (1980). At low frequencies the results compare more favourably with BS 6841 (1987) (W_b frequency weighting) than ISO 2631/DAD1 (1980). However, at high frequencies the results suggested lower acceleration magnitudes corresponded to perception thresholds than both standards.

A second study was conducted by Parsons (1982) to determine the z–axis perception threshold of sitting subjects in the frequency range 2 to 89.6 Hz. The stimuli consisted of sinusoidal motion and $^1/_3$–octave, 1–octave and 5–octave bands of random motion. There was no significant difference between the r.m.s. acceleration magnitude of the thresholds of $^1/_3$–octave and sinusoidal motion. The threshold for sinusoidal motion is shown in Figure 2.4.1. The results suggest a much greater frequency dependence than those obtained in the earlier study (Parsons, 1981). The author did not suggest a reason for the difference between the results of the two studies. The difference may have been due to the very different experimental techniques employed. At frequencies greater than 4 Hz the results were similar to the threshold proposed in the British Standard (BS 6841, 1987), although they indicate slightly greater sensitivity to acceleration than the British Standard.

A further study was conducted by Parsons (1983) to determine perception thresholds of sitting, standing and recumbent subjects exposed to x-axis and y-axis vibration. The subjects were presented with sinusoidal whole-body motion and were asked to adjust the magnitude of the vibration until they could just feel the vibration. Lateral (y-axis) and fore-and-aft (x-axis) motion were presented separately to sitting and standing subjects in the frequency range 2 Hz to 100 Hz. The results indicated no significant difference between x-axis and y-axis thresholds except at 16 Hz for sitting subjects and 31.5 Hz for standing subjects. ISO 2631/DAD1 (1980) and BS 6841 (1987) also suggest the thresholds for x-axis and y-axis motion are the same. The difference between the thresholds of sitting and standing subjects was significant for x-axis and for y-axis motion. The results obtained by averaging over the two horizontal axes are shown for sitting and standing subjects in Figure 2.4.2. The results suggest that the thresholds proposed in ISO 2631/DAD1 (1980) overestimate the sensitivity to acceleration except at frequencies above 40 Hz. The results compare more favourably with the British Standard 6841 (1987) for frequencies up to 16 Hz. Above this frequency the threshold was at lower acceleration magnitudes than suggested by the British Standard.

The perception threshold was also determined of recumbent subjects exposed to vertical (x-axis) motion in the frequency range 10 Hz to 63 Hz. The results are shown in Figure 2.4.3 and show some support for the threshold proposed by the British Standard 6841 (1987) although above 40 Hz the standard may underestimate the sensitivity of recumbent subjects to acceleration and below 40 Hz overestimate the sensitivity of recumbent subjects.

2.4.2.9 Miwa, Yonekawa and Kanada (1984)

Ten recumbent men were exposed to vertical (x-axis) and horizontal (z-axis and y-axis) whole-body vibration in a study conducted by Miwa, Yonekawa and Kanada (1984) to determine perception thresholds. The subjects were presented with motion in the frequency range 1 Hz to 100 Hz. The stimuli consisted of continuous motion, single-cycle shocks and multi-cycle pulses. Each motion was increased in magnitude in 2 dB steps until the vibration was perceived and then decreased until the subjects indicated it could no longer be felt. The subjects judged whether the vibration was perceptible after ten seconds of continuous motion, three single cycle shocks at five-second intervals or two multi-cycle pulses of vibration at five-second intervals.

The average threshold for vertical (x-axis) motion is shown in Figure 2.4.3. The results indicate support for the threshold proposed by BS 6841 (1987) except at frequencies greater than 20 Hz, when the results suggest BS 6841 underestimates the sensitivity of recumbent subjects to vertical acceleration. The results are similar to those obtained in a study by Parsons (1983).

Figure 2.4.4 shows the average threshold of recumbent subjects exposed to horizontal (y-axis) motion. The results are similar to those obtained by Reiher and Meister (1931) and at frequencies from 4 Hz to 30 Hz support the thresholds proposed by ISO 2631/DAD1 (1980).

2.4.3 Discussion and Conclusions

Figures 2.4.1 and 2.4.2 show perception thresholds of sitting and standing subjects exposed to vertical and horizontal motion respectively. Figures 2.4.3 and 2.4.4 show thresholds of recumbent subjects exposed to vertical and horizontal motion. The figures are adapted from the studies reviewed in Section 2.4.2. The findings of the studies are compared with the thresholds proposed by the Draft Addendum ISO 2631/DAD1 (1980) and with asymptotic approximations of the thresholds proposed in the British Standard 6841 (1987). The figures illustrate the large differences between the findings of the studies. Several of the studies employed unconventional methods of experimentation or analysis. For example, Jacklin and Liddell (1933) employed an experimental technique involving repetition of the procedure until a required result was obtained, elimination of "out of line" points and the inclusion of the effect of vision in the definition of "perceptible". Gorrill and Snyder (1957) instructed subjects to perform a signal tracking task during the determination of perception thresholds. The thresholds determined by Chaney (1964, 1965) were at such large magnitudes that they cannot be considered valid.

The remaining studies resulted in thresholds of the same order. For sitting and standing subjects exposed to vertical motion, the findings of Benson and Dilnot (1981), Reiher and Meister (1931) and Parsons (1982) indicate support for the perception threshold proposed in BS 6841 (1987). The findings of McKay (1971) and Parsons (1981) suggest both standards underestimate the sensitivity to acceleration at high frequencies. At frequencies less than 40 Hz, most studies determined perception thresholds of magnitudes greater than the threshold proposed by ISO 2631/DAD1 (1980).

For sitting and standing subjects exposed to horizontal motion, the frequency dependence of the thresholds from all the studies are in general agreement with the standards although the findings of Parsons (1983) suggest the standards underestimate the sensitivity to acceleration at high frequencies.

The Draft Addendum ISO 2631/DAD1 (1980) proposes that the threshold of recumbent subjects exposed to vertical (x–axis) motion will be the same as for sitting and standing subjects exposed to horizontal (x–axis) motion. The standard proposes that the threshold of recumbent subjects exposed to horizontal (z–axis) motion will be the same as for sitting and standing subjects exposed to vertical (z–axis) motion. Contrary to these proposals, the British Standard 6841 (1987) tentatively proposes that the threshold of recumbent subjects exposed to vertical (x–axis) motion will be the same as for sitting and standing subjects exposed to vertical (z–axis) motion (W_b frequency weighting) and the threshold of recumbent subjects exposed to horizontal (z–axis) motion will be the same as for sitting and standing subjects exposed to horizontal (x–axis) motion (W_d frequency weighting).

A small number of studies were conducted to determine thresholds of recumbent subjects. From two studies conducted by Reiher and Meister (1931) and Miwa, Yonekawa and Kanada (1984), perception thresholds were obtained of recumbent subjects exposed to horizontal (y–axis) motion. The results in the frequency range 4 Hz to 30 Hz were similar to the proposed threshold of ISO 2631/DAD1 (1980) for this axis (see Figure 2.4.4). Four studies were conducted to determine thresholds of lying subjects exposed to vertical (x–axis) motion. The findings of the three studies show little agreement (see Figure 2.4.3). The findings of Reiher and Meister (1931) suggest support for ISO 2631/DAD1 (1980). Parsons (1983) and Miwa et al (1984) found thresholds which were more consistent with the British Standard 6841 (1987). The findings of Miwa and Yonekawa (1971) show little support for either standard.

Several authors compared the thresholds of subjects adopting different postures. McKay (1971) found that, for frequencies from 1.5 Hz to 100 Hz, seated subjects were generally more sensitive to vertical acceleration than standing subjects, except between 15 Hz and 25 Hz, when standing subjects were more sensitive. Parsons (1981) also found that seated subjects were more sensitive than standing subjects to vertical acceleration at frequencies less than 8 Hz. While above 16 Hz, subjects were more sensitive when standing. A second study by Parsons (1983) involving horizontal motion from 2 Hz to 89.6 Hz showed that seated subjects were more sensitive than standing subjects to acceleration at frequencies less than 16 Hz. Recumbent subjects were generally more sensitive to horizontal acceleration than sitting or standing subjects.

There are large differences between the perception thresholds determined in the studies reviewed. However, for sitting and standing subjects exposed to horizontal and vertical motion, the results suggest the thresholds proposed in the Draft Addendum ISO 2631/DAD1 (1980) overestimate the sensitivity to whole-body vibration acceleration. The thresholds proposed in the British Standard (BS 6841, 1987) compare more favourably with the findings of the studies reviewed than ISO 2631/DAD1 (1980). However, there is some evidence that the thresholds at high frequencies may be at lower acceleration magnitudes than suggested in the standard. A few studies determined thresholds of recumbent subjects but there was little agreement between the findings of these studies.

2.5 COMPARISON OF PERCEPTION THRESHOLDS AND COMFORT CONTOURS

2.5.1 Introduction

The objective assessment of building vibration requires knowledge of the relative disturbance produced by different frequencies at low magnitudes. Some standards, for example, International Standard ISO 2631/DAD1 (1980) and British Standard 6841 (1987), propose that the frequency dependence of the threshold of perception is the same as the frequency dependence of reaction to vibration at all magnitudes of perceptible motion. Vibration induced in buildings by passing trains is generally at low magnitudes, at or just above the threshold of perception, therefore, the determination of the frequency dependence of reaction to building vibration must consider both the perception threshold and equal comfort contours. This section reviews the small number of studies which have compared perception thresholds and comfort contours for whole-body translational vibration in the same experiment. The aim of this section is to determine whether there is experimental evidence to show that frequency weightings for high magnitude vibration may also be applied to low magnitude building vibration. The studies are reviewed in chronological order.

2.5.2 Relevant Studies

2.5.2.1 Reiher and Meister (1931)

Perception thresholds and equal comfort contours for vertical (z-axis), lateral (y-axis) and fore-and-aft (x-axis) whole-body vibration were determined in a study by Reiher and Meister (1931). The method of semantic scaling was employed. Ten subjects adopted sitting, standing and recumbent postures and were presented with sinusoidal vibration in the frequency range 3 Hz to 70 Hz. After five minutes exposure to each stimulus, the subjects were instructed to respond with one of six adjectives:

> "Not perceptible
> Weakly perceptible
> Easily perceptible
> Strongly perceptible
> Unpleasant, believed dangerous for long periods
> Very unpleasant, believed dangerous for short periods".

The amplitude of motion as a function of frequency was shown on separate figures for each axis of motion and for each posture. Each individual data point corresponded to one of the semantic ratings. Boundary curves were drawn between groups of data points to illustrate the division of the results into six domains corresponding to the six semantic ratings. The lowest boundary, which divided the two ratings described by "not perceptible" and "weakly perceptible", was described as the threshold of perception. The method employed to determine the position of the boundaries was not described. The authors suggested the curves may be described by the equation $an^k = c$, where a is the amplitude, and n is the frequency. The exponent, k, and the constant, c, depended on which boundary was considered. Reiher and Meister suggested the value of the exponent, k, increased with the magnitude of the stimulus, beginning at unity at the threshold of perception. This implies that the criterion of perception is velocity dependent, but that for equal comfort contours, as the magnitude of vibration increases, subjective reaction becomes more acceleration dependent. The results for each axis and posture were similar. Figure 2.5.1 is adapted from Reiher and Meister (1931) and shows the vibration acceleration as a function of frequency corresponding to each boundary for recumbent subjects exposed to vertical (x–axis) motion. The figure suggests that at low magnitudes sensitivity to acceleration was greatest at low frequencies and gradually decreased with increasing frequency. While at high acceleration magnitudes, sensitivity to acceleration gradually increased with increasing frequency. Such a difference between the perception threshold and equal comfort contours cannot be considered as proven by the results, since the method of determining the position of the boundary curves was not defined.

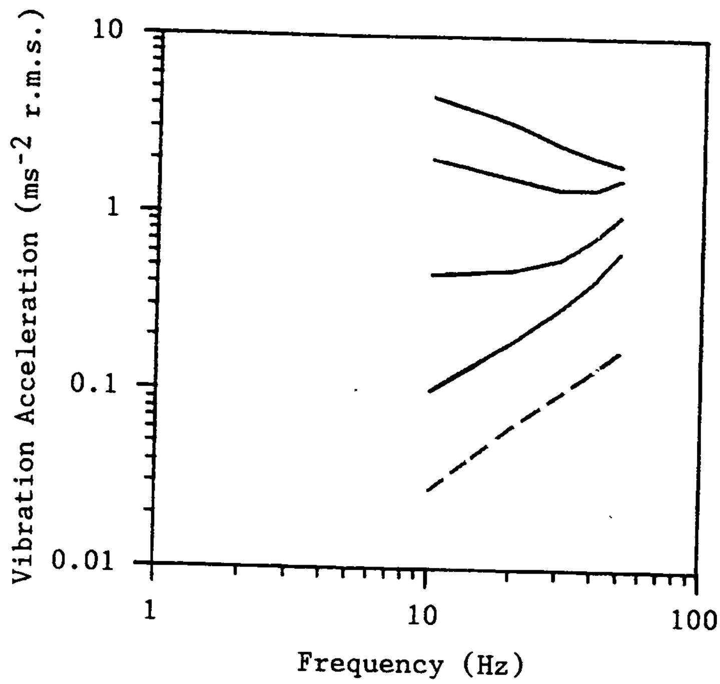

Figure 2.5.1 Perception threshold (----) and comfort contours (——) for recumbent subjects exposed to vertical (x-axis) vibration. Adapted from Reiher and Meister (1931).

2.5.2.1 Jacklin and Liddell (1933)

Perception thresholds and equal comfort contours for subjects exposed to x-axis, y-axis and z-axis motion were determined by Jacklin and Liddell (1933) by use of three semantic labels:

> "Perceptible
> Annoying or disturbing
> Very uncomfortable, painful or unbearable".

Approximately one hundred seated subjects were presented with selected amplitudes of sinusoidal whole-body vibration which gradually increased in frequency. The subjects employed the semantic labels to describe their response to the stimuli. It may be necessary to regard the results of the study with some discretion for several reasons. First, the experimental method was rather unconventional. A histogram for each amplitude was continuously constructed to indicate the number of subjects at each frequency of motion responding with a specific semantic label. The experiment was repeated with new subjects until the histogram indicated at least one half of the total readings fell within 20% above or below the final average value. Points "out of line" were rechecked with more subjects. A method which involves the repetition of the procedure until a specific result occurred cannot be considered as satisfactory. The definitions of the three semantic labels may have been a source of error and confusion. "Perceptible" was defined in terms of the effect of vibration on vision: "You now feel that you are moving or that distant objects are moving slightly or becoming hazy." The other two semantic labels, "annoying or disturbing" and "very uncomfortable, painful or unbearable" apparently caused some confusion since some subjects selected the "disturbing" label as corresponding to higher magnitudes than the "uncomfortable" label, while other subjects selected the "uncomfortable" label for higher magnitudes. It is evident that a different choice of semantic labels and definitions may have provided different results.

2.5.2.3 *Gorrill and Snyder (1957)*

A study by Gorrill and Snyder (1957) involved the use of five semantic labels to describe the response of seated subjects to vertical sinusoidal whole-body vibration at frequencies between 3 Hz and 30 Hz. The semantic labels described the degree of perception, annoyance or tolerance evoked by the vibration:

> "Threshold of perception
> Definitely or easily perceptible
> Irritating or annoying
> Maximum tolerable for continuous operation
> Intolerable".

Figure 2.5.2 is adapted from Gorrill and Snyder (1957) and shows the mean acceleration as a function of frequency corresponding to each of the five semantic labels. The shape of each contour is fairly similar, although there may be some evidence that at low acceleration magnitudes subjects were more sensitive to high frequencies while at high acceleration magnitudes subjects were more sensitive to low frequencies. However, the change in the frequency dependence is not very marked. The high magnitudes of acceleration for the perception threshold, compared with other studies (see Section 2.4), create doubt about the validity of findings and may have been a result of the subjects performing a signal tracking task during the experiment.

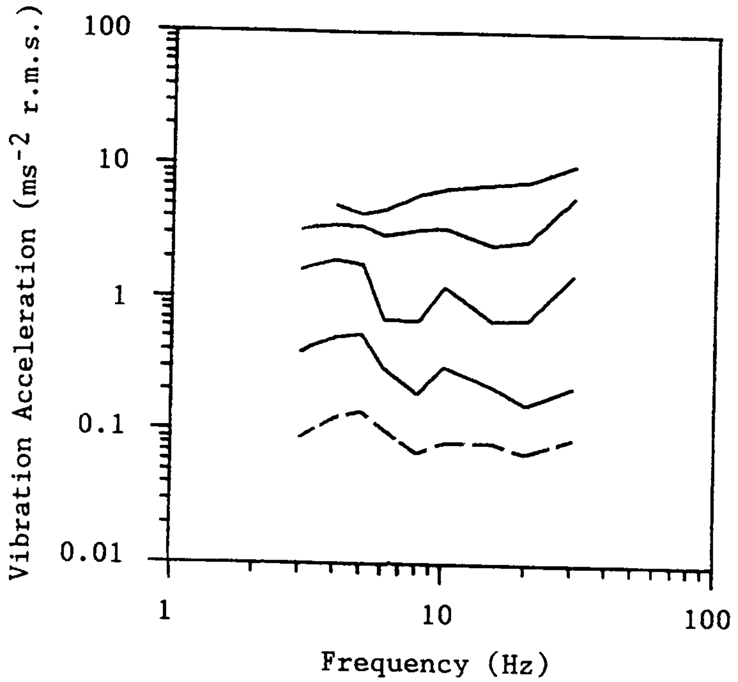

Figure 2.5.2 Perception threshold (----) and comfort contours(——) for sitting subjects exposed to vertical (z-axis) vibration. Adapted from Gorrill and Snyder (1957).

2.5.2.4 *Chaney (1964, 1965)*

Perception thresholds and equal comfort contours resulting from a study by Chaney (1964) are shown in Figure 2.5.3. Two studies were conducted which involved sitting subjects (Chaney, 1964) and standing subjects (Chaney, 1965). Subjects were exposed to sinusoidal vertical whole-body vibration in the frequency range 1 Hz to 27 Hz. The magnitude of the test stimulus was adjusted by the subject until it produced a response corresponding to one of four ratings:

"Perceptible
Mildly annoying
Extremely annoying
Alarming".

The results for sitting subjects suggested that the perception threshold was not frequency dependent. However, the equal comfort contours indicated that a frequency dependence did exist for sensitivity to vibration at high acceleration magnitudes. This implies that at low acceleration magnitudes, response to whole-body vibration was independent of frequency, but as the acceleration magnitude increased the subjective magnitude became more frequency dependent, with maximum sensitivity to acceleration between about 4 Hz and 10 Hz. The results for standing subjects showed a similar trend (Chaney, 1965). The perception thresholds for both sitting and standing subjects were at much greater acceleration magnitudes than suggested by other studies (see Section 2.4) and this may lead to uncertainty about the validity of the results.

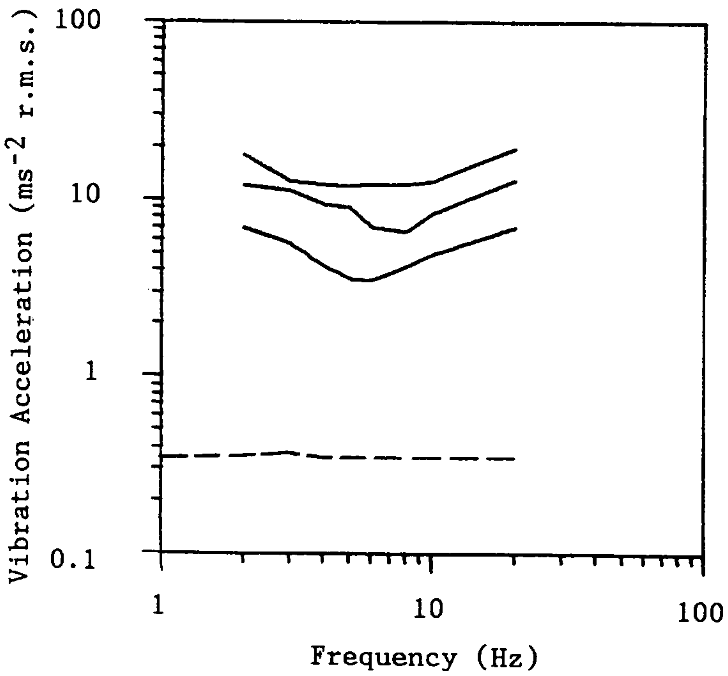

Figure 2.5.3 Perception threshold (----) and comfort contours (——) for sitting subjects exposed to vertical (z-axis) vibration. Adapted from Chaney (1964).

2.5.2.5 *Simic (1970)*

Perception thresholds were determined, in a study by Simic (1970), for sitting subjects exposed to vertical motion in the frequency range 0.1 Hz to 30 Hz. The amplitude of sinusoidal motion was gradually increased until the stimulus was perceived. Equal comfort contours were determined using the prediction method. Subjects indicated the magnitude of vibration they would tolerate for a certain exposure duration (e.g. 10 minutes, 1 hour or 4 hours). The perception threshold and comfort contours showed a similar effect of frequency and indicated minimum sensitivity acceleration between 2 Hz and 3 Hz and maximum sensitivity to acceleration at 15 Hz. There is some similarity between the findings of Simic (1970) and Miwa and Yonekawa (1971), however, the prediction method is not considered reliable. It is very likely that subjects will respond with lower magnitudes for longer durations but the judgement may not be based on any experience. Another possible source of error was the use of a soft seat, since it is not clear whether the acceleration at the seat/man interface was employed in the analysis of the results.

2.5.2.6 Miwa and Yonekawa (1971)

Matching methods were employed by Miwa and Yonekawa (1971) to determine equal comfort contours for z–axis and x–axis sinusoidal whole–body vibration in the frequency range 0.5 Hz to 300 Hz. Sitting, standing and recumbent subjects were presented with a 20 Hz fixed magnitude reference motion, followed by a test stimulus. The subjects adjusted the test stimulus until it produced a subjective magnitude equal to the reference stimulus. The perception threshold was also determined during the experiment. Subjects were exposed repeatedly to constant amplitude sinusoidal motion followed by a pause. After each pause the stimulus was increased by 0.1 dB. Figure 2.5.4 is adapted from Miwa and Yonekawa (1971) and shows the mean perception threshold and four equal comfort contours corresponding to acceleration equivalent to four magnitudes of 20 Hz motion. The figure shows the combined results from sitting and standing subjects exposed to vertical motion. The contours, which were fitted approximately to the results, are comprised of gradients of –6 dB/octave, 0 dB/octave, +6 dB/octave and +12 dB/octave, corresponding to constant jerk, acceleration, velocity and displacement respectively. For vertical and for horizontal motion, the shapes of the four equal comfort contours were similar. Maximum sensitivity to acceleration occurred between 4 Hz and 7 Hz for vertical motion and between 0.5 Hz and 2 Hz for horizontal motion. The perception threshold exhibited similar frequency dependence to the comfort contours, although for perception a section of constant sensitivity to acceleration occurred between about 40 Hz and 100 Hz. The results suggest that the frequency dependence of subjective response to whole–body vibration did not depend on the magnitude of the acceleration and that the perception threshold varied with frequency in a similar manner to comfort contours.

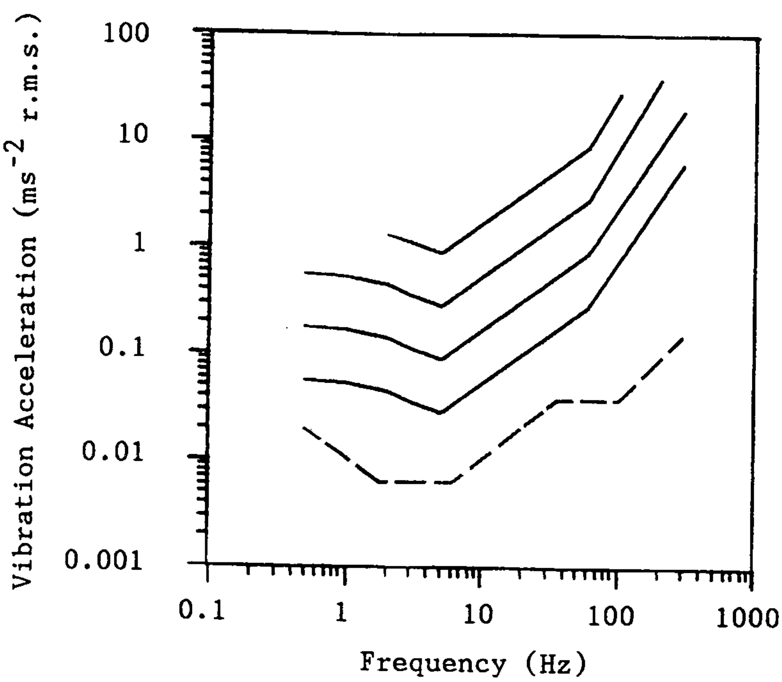

Figure 2.5.4 Perception threshold (----) and comfort contours (——) for sitting and standing subjects exposed to vertical (z–axis) vibration. Adapted from Miwa and Yonekawa (1971).

2.5.3 Discussion and Conclusions

The results of the studies reviewed show little agreement when comparing perception thresholds and comfort contours. Reiher and Meister (1931) suggested that for perception thresholds and comfort contours at low acceleration magnitudes, sensitivity to acceleration was greatest at low frequencies, while at high magnitudes sensitivity was greatest at high frequencies. The findings of Gorrill and Snyder (1957) suggested an opposite effect of magnitude on frequency dependence, with greater sensitivity to high frequencies at low acceleration magnitudes but greater sensitivity to low frequencies at high acceleration magnitudes. However, the change in the shape of the comfort contours with magnitude was not very marked. Chaney (1964, 1965) found that perception thresholds were independent of frequency while equal comfort contours corresponding to three semantic ratings showed an increase in sensitivity to acceleration between about 3 Hz and 10 Hz. Results from Miwa and Yonekawa (1971) suggested that the effect of frequency on perception thresholds and equal comfort contours did not depend on the acceleration magnitude of vibration. This is in accordance with the Draft Addendum ISO 2631/DAD1 (1980) and BS 6841 (1987) which propose that the frequency dependence of the perception threshold is the same as the frequency dependence of the subjective reaction to whole–body vibration at all acceleration magnitudes of perceptible vibration.

A reason for the disagreement between findings of studies comparing perception thresholds and comfort contours may be attributed to the different experimental techniques employed. It may be argued that, when comparing perception thresholds and comfort contours, the same experimental method should be employed to determine perception thresholds as to determine comfort contours. This would eliminate the studies by Miwa and Yonekawa (1971) and Simic (1970). The remaining studies employed semantic rating to determine perception thresholds and comfort contours. In the study by Reiher and Meister (1931), boundary curves were drawn separating data points corresponding to each semantic category. However, the method of determining the position of the boundary curves was not defined. Jacklin and Liddell (1933) provided definitions of the semantic labels employed in their study. However, the definitions were a source of confusion amongst some subjects. The method employed in their study, which involved repetition of the procedure until a specific result occurred, may also be considered unsatisfactory. The studies by Gorrill and Snyder (1957) and Chaney (1964, 1965) resulted in perception thresholds which were much higher than suggested by other studies (see Figure 2.4.1). This may indicate that their results should be considered with some discretion.

This section has shown that there is too little experimental data available on which to judge whether frequency weightings for high magnitude vibration may also be applied to low magnitude vibration of the type which might occur in buildings. Only three of the studies exposed subjects to horizontal motion (Reiher and Meister (1931), Jacklin and Liddell (1933) and Miwa and Yonekawa (1971)). In order to quantify the effect of railway-induced building vibration, it is evident that investigations are required to determine frequency weightings for low magnitude vertical and horizontal motion.

2.6 THE SUBJECTIVE EQUIVALENCE OF NOISE AND WHOLE-BODY VIBRATION: A REVIEW OF PREVIOUS INVESTIGATIONS

2.6.1 Introduction

There have been many experimental investigations into the subjective reaction to noise and vibration. A major proportion of these studies have investigated either of the two stimuli separately. Recommendations for acceptable levels of noise and limits for vibration have been proposed based on the results of independent studies. Exposure to building vibration caused by the passage of nearby trains very often occurs simultaneously with exposure to railway noise, therefore, to quantify the effect of railway-induced building vibration, the relative importance of the two stimuli must be considered.

This section is concerned with studies of subjective reaction to noise and whole-body vibration. Five studies are reviewed which were conducted to determine the relative importance of noise and vibration by determining the subjective equivalence of the two stimuli. The relation between noise and vibration was determined by the authors of each study in terms of the sound pressure level and the root-mean-square acceleration. However, these measures do not allow for the effect of the duration, direction and frequency of the two stimuli. A relation between one type of noise and one vibration stimulus cannot be used to predict the equivalence between different noise and vibration stimuli unless the relation allows for the effect of these variables. The vibration dose value, VDV, ($(\int_0^T a^4(t)\,dt)^{1/4}$ where a(t) is the frequency weighted acceleration) provides a means of quantifying vibration stimuli which allows for the effect of magnitude, direction, frequency and duration. The vibration dose value can be considered as the root-mean-quad acceleration magnitude of an equivalent one second stimulus. An equivalent method of quantifying a noise stimulus is the sound exposure level, L_{AE}, which is defined in Appendix 2. An expression in terms of the vibration dose value and the sound exposure level, which indicates the levels of noise and vibration which produce equal reaction, may be used to predict the relative importance of different types of noise and vibration.

According to Steven's psychophysical law, the subjective magnitudes of sound and vibration, ψ_s and ψ_v, are related to the physical magnitudes of the stimuli, φ_s and φ_v, by the following expressions:

$$\psi_s = k_s \varphi_s^{n_s}, \qquad \psi_v = k_v \varphi_v^{n_v}$$

where k_s, k_v, n_s and n_v are constants. Thus, the subjective equivalence between noise and vibration may be expressed by:

$$k_s \varphi_s^{n_s} = k_v \varphi_v^{n_v}$$

where the value of the sound exponent, n_s, is usually 0.67 when φ_s is sound pressure, p, (Stevens, 1986) i.e:

$$\psi_s = k_s p^{0.67}$$

and $$\log \psi_s = 0.67 \log p + \log k_s$$

But sound pressure level, SPL is given by:

$$SPL = 20 \log_{10} \left[\frac{p_{rms}}{p_{ref}}\right]$$

so $$\log_{10} \psi_s = 0.67 \frac{SPL}{20} + \log_{10} k_s$$

therefore $$\log_{10} \psi_s = 0.033 \, SPL + \log_{10} k_s$$

Hence, the sound pressure level, SPL, may be related to the vibration magnitude by the expression:

$$0.033 \, SPL = n_v \log_{10} \varphi_v + k$$

and $$0.033 \, L_{AE} = n_v \log_{10} VDV + k'$$

This review involves the determination of the equivalence between noise and vibration in terms of the vibration dose value, VDV, and the sound exposure level, L_{AE}, from the results reported by the authors in terms of the sound pressure level and the root-mean-square acceleration. This enables a comparison of the results from various studies despite the investigations involving different types of stimuli. The equivalence between noise and vibration provides information on which to decide whether the reduction of noise or the reduction of vibration would be more likely to reduce discomfort or disturbance. The studies are reviewed in chronological order.

2.6.2 Relevant Studies

2.6.2.1 Hempstock and Saunders (1972, 1973)

A study was conducted by Hempstock and Saunders (1972) in which broad band noise (30 to 5 kHz) was matched with random vertical whole-body vibration (3 to 25 Hz). Eight seated subjects were presented with alternate 2.5 second exposures of noise and vibration and were asked to indicate whether the noise stimulus was subjectively greater or less than the vibration. After each presentation the experimenter adjusted the noise to a level nearer equivalence. Eight subjects were tested once at five vibration magnitudes. Five subjects were tested five times with one day elapsing between tests. The mean noise levels (S.P.L. dB) corresponding to the five vibration magnitudes (g r.m.s.) were reported. The results demonstrated that although individuals made consistent judgements, there was large intersubject variability. Judgements were consistent when the test was repeated over a number of days.

In a later study, the cross-modality method was employed by Hempstock and Saunders (1973) to determine the growth function for the effect of magnitude of whole-body vibration on subjective response. A relation describing the subjective equivalence between noise and vibration was evolved and was used to determine the exponent, n, relating the subjective response, ψ, and the magnitude of vibration, φ, in the form of a power function, $\psi = k\varphi^n$. The subjects matched $^1/_3$-octave band random noise centred at 2 kHz with sinusoidal motion at frequencies ranging from 5 Hz to 80 Hz. Each stimulus was presented for 2.5 seconds. In one session, subjects altered the magnitude of a vibration stimulus to be subjectively equivalent to a noise stimulus which was fixed at one of five levels. In a second session, subjects altered a noise stimulus to the level which produced the same sensation as a vibration stimulus fixed at one of five magnitudes. If the matching required the variable stimulus to be increased to a level beyond the capability of the apparatus the test was discontinued and the result was discarded. The direction of vibration was not reported.

The results were employed by the authors to determine a relation describing the equivalence between noise and vibration of the form:

$$p = s \log_{10} a + b$$

where p is the sound pressure level (dB(A)),
a is the root-mean-square acceleration (g),
s and b are constants.

(The values of s and b determined at each frequency were provided for each session.)

The equivalence between noise and vibration can be determined in a more useful form given by:

$$L_{AE} = s \log_{10} VDV + k \qquad (2.6.1)$$

where L_{AE} is the sound exposure level (dB(A)),
VDV is the vibration dose value ($ms^{-1.75}$),
s and k are constants.

The relation given by Equation 2.6.1 provides a measure of the relative importance of noise and vibration which allows for the effect of frequency and duration of the two stimuli. Further analysis may be applied to the data provided by the authors to determine the equivalence between noise and vibration in the form of Equation 2.6.1. This involves the transformation of r.m.s. acceleration magnitudes to vibration dose values by making the assumption that vertical motion was presented and therefore W_b frequency weighting is appropriate (BS 6841, 1987).

Table 2.6 shows the values of s and k in Equation 2.6.1 which may be obtained for each session for the six frequencies presented in the experiment.

Vibration fixed stimulus			Noise fixed stimulus		
Frequency (Hz)	s	k	Frequency (Hz)	s	k
6	15.8	86.7	5	47.6	73.7
10	15.8	85.0	10	37.0	73.0
16	16.8	81.2	20	45.5	70.4
25	16.4	84.5	30	43.5	75.3
40	20.1	88.0	40	40.0	82.3
80	17.2	90.6	80	47.6	92.7

Table 2.6 The values of s and k in the relation $L_{AE} = s \log_{10} VDV + k$ determined by further analysis of the results presented by Hempstock and Saunders (1973).

The results indicated that an increase in the vibration magnitude corresponded to a much smaller increase in noise level with vibration as the fixed stimulus than with noise as the fixed stimulus. Figure 2.6 shows the equivalence curves for the two sessions determined by averaging over the six frequencies. The equivalence between noise and vibration is illustrated for the range of vibration dose values employed in the experiment. The average equivalence curve for the session in which vibration was the fixed stimulus was given by:

$$L_{AE} = 17.0 \log_{10} VDV + 86.0$$

For noise as the fixed stimulus the average equivalence curve was given by:

$$L_{AE} = 43.5 \log_{10} VDV + 77.9$$

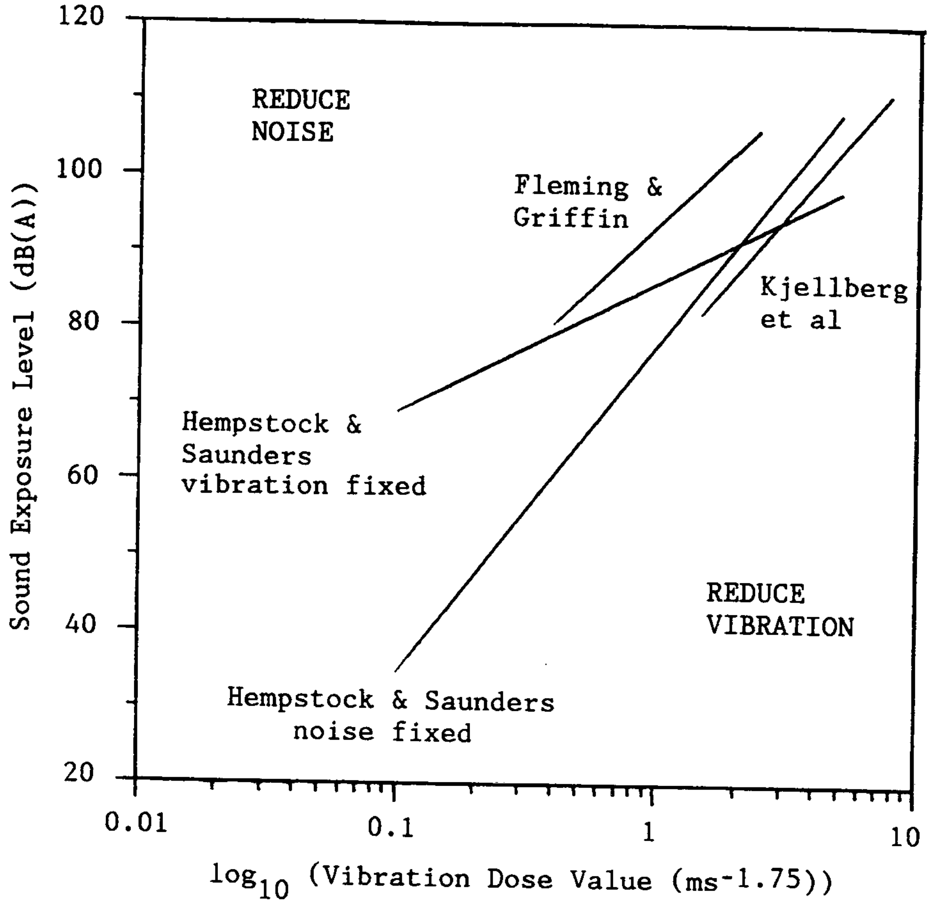

Figure 2.6 A comparison of the subjective equivalence between noise and vibration from three studies.

Hempstock and Saunders (1973) concluded that the results obtained from cross–modality matching depended on which stimulus was fixed. The authors did not provide an explanation of the difference between the results of the two sessions. However, Stevens (1959) reported a similar effect with cross–modality matching of noise and vibration and referred to it as the "regression effect". It is apparent in many kinds of matching experiments and may be regarded as a tendency for the subjects to reduce the range of whichever variable they are allowed to adjust. The subjects tend to regress towards the mean, that is, there is a centering of the results. To determine the exponent, n, in the power function, $\psi = k\varphi^n$, Hempstock and Saunders employed a relation between noise and vibration obtained by averaging the results of the session in which vibration was the fixed stimulus and the session in which noise was the fixed stimulus. The authors described the average equivalence between noise and vibration in terms of sound pressure level and r.m.s. acceleration. However, the relation may be written as:

$$L_{AE} = 30.3 \log_{10} VDV + 82.0$$

or

$$0.033\ L_{AE} = 1.00\ \log_{10} VDV + 2.71$$

Some uncertainty about the results may exist due to the elimination of some data because of the restricted capability of the apparatus.

2.6.2.2 Clarke and Oborne (1975a)

A study was conducted by Clarke and Oborne (1975a) to assess the technique of cross-modality matching of noise and vibration. Twelve subjects matched pure tone noise at 250 Hz and 1000 Hz and a broad band low frequency noise with whole-body vibration. Individual hearing thresholds were measured and were employed to determine the equivalence between noise level above threshold and vibration acceleration. The results were similar for the three noise types. Interpretation of the results is limited because the frequency, axis and duration of the vibration stimuli and the hearing thresholds were not reported.

2.6.2.3 Fleming and Griffin (1975)

An experiment was conducted by Fleming and Griffin (1975) to determine the subjective equivalence between 1 kHz pure tone noise and 10 Hz sinusoidal whole-body vertical vibration. Twenty seated subjects were presented with all 64 combinations of eight levels of noise (65 dB to 100 dB SPL) and eight magnitudes of vibration (0.2 ms^{-2} r.m.s. to 1.2 ms^{-2} r.m.s.). The noise and vibration were presented simultaneously for 10 seconds. After each presentation the subjects indicated which of the stimuli, noise or vibration, they would prefer to be reduced. The results were used to determine the levels of noise and vibration at which 50% of the subjects indicated a preference for the reduction of noise and 50% indicated a preference for the reduction of vibration. This provided the 50th percentile for the preference of reduction of noise, which was interpreted as the subjective equivalence of noise and vibration. Linear regression analysis of the 50th percentile yielded a relation for the subjective equality between noise and vibration. The authors expressed the relation as:

$$0.03\ SPL = 0.99\ \log_{10} \varphi_v + 2.77$$

where SPL is the sound pressure level of the noise (dB(A)) and φ_v is the objective magnitude of the vibration (ms^{-2} r.m.s.).

However, the relation may also be expressed in terms of the sound exposure level, SEL (dB(A)) and the vibration dose value, VDV ($ms^{-1.75}$):

$$0.033\ L_{AE} = 1.09 \log_{10} VDV + 3.09$$

The curve of subjective equivalence is shown in Figure 2.6 for the range of vibration magnitudes presented to the subjects.

2.6.2.4 *Kjellberg, Wikstrom and Dimberg (1985)*

The subjective equivalence of noise and vibration was employed by Kjellberg, Wikstrom and Dimberg (1985) to investigate the effect of vibration exposure time on discomfort. The first part of the study involved cross-modality matching and required fifteen seated men to adjust broad band noise to the level at which it gave rise to the same discomfort as whole-body vertical vibration. Two types of vibration stimuli were employed in the experiment. These were recordings on the floor of a 12 ton forklift truck and a 1.5 ton forklift truck. The vibration recorded in the 12 ton truck contained energy mainly at 3.1 Hz. Vibration in the 1.5 ton truck was mostly at 6.3 Hz. The vibration stimuli were presented for six seconds each and at four acceleration magnitudes. The noise stimuli were presented simultaneously with the vibration, but were continued for a further two seconds after termination of the vibration. The mean sound pressure levels (dB) giving rise to the same discomfort as the vibration (log ms^{-2} r.m.s.) were shown for each frequency. Kjellberg et al reported large variations between the individual regression coefficients of sound pressure level (dB) as a function of the vibration acceleration (log ms^{-2} r.m.s.). The subjective equivalence of noise and vibration may be determined in terms of the sound exposure level (dB(A)) and the vibration dose value ($ms^{-1.75}$) by further analysis of the data reported by the authors. The $^1/_3$-octave spectrum of the sound provided by Kjellberg et al may be employed to transform the reported mean sound pressure level settings (dB) to sound exposure levels (dB(A)). To determine the vibration dose values from the ISO 2631 weighted acceleration reported, the assumption can be made that all energy was at frequencies of 3.1 and 6.3 Hz for the two vibration stimuli. If the root-mean-square acceleration magnitudes are frequency weighted (W_b), the estimated vibration dose value can be determined (Griffin, 1984). Linear regression analysis results in the following expression for the subjective equivalence of noise and vibration:

$$L_{AE} = 40.0 \log_{10} VDV + 75.5$$

The equivalence curve is compared with the curves from Hempstock and Saunders (1973) and Fleming and Griffin (1975) in Figure 2.6.

2.6.3 Discussion and Conclusions

For three of the studies reviewed a relation was determined for the equivalence of noise and vibration of the form:

$$n_s\, L_{AE} = n_v \log_{10} VDV + k'$$

If the value of the exponent for noise, n_s, is assumed to be 0.033, the value of the exponent for vibration, n_v, may be obtained.

With noise as the fixed stimulus, the study by Hempstock and Saunders (1973) resulted in the following relation:

$$0.033\, L_{AE} = 0.56 \log_{10} VDV + 2.84$$

The relation obtained when vibration was fixed may be expressed as:

$$0.033\, L_{AE} = 1.44 \log_{10} VDV + 2.57$$

The equivalence between noise and vibration obtained by combining the results of the two sessions may be described by:

$$0.033\, L_{AE} = 1.00 \log_{10} VDV + 2.71$$

This indicates a value of 1.00 for the vibration exponent, n_v. The relation obtained by Fleming and Griffin (1975) ($0.033L_{AE} = 1.09 \log_{10} VDV + 3.09$) suggests a value of 1.09 for the exponent for vibration. A value of 1.32 was obtained from the results of Kjellberg et al (1985). They determined the subjective equivalence of noise and vibration as:

$$0.033\, L_{AE} = 1.32 \log_{10} VDV + 2.49$$

A value of about 1.0 for the vibration exponent agrees with results obtained in other studies (see Section 2.2).

A comparison of the curves of subjective equality between noise and vibration from studies exposing subjects to different types of stimuli can be obtained from Figure 2.6. The two curves from the study by Hempstock and Saunders (1973) correspond to the matching of noise to a fixed vibration stimulus and the matching of vibration to a fixed noise stimulus. The two sessions provided very different results at low magnitudes. For example, a vibration dose value of 0.1 $ms^{-1.75}$ corresponded to a sound exposure level of 34.5 dB(A) when noise was the fixed stimulus but to 69 dB(A) when vibration was the fixed stimulus. The authors proposed combining the results of the two methods.

Kjellberg et al determined the equivalence between noise and vibration in a study which involved matching noise to fixed vibration stimuli. Surprisingly, their results were more similar to those of Hempstock and Saunders (1973) with noise as the fixed stimulus than the results obtained when the vibration was fixed. The results obtained by Fleming and Griffin (1975) suggest much higher noise levels equivalent to a particular vibration magnitude than Kjellberg et al (1985) and Hempstock and Saunders (1973). The most likely reason for the conflicting results is the different experimental techniques employed.

The studies reviewed in this section have indicated similar ratios between the growth functions for noise and vibration (n_v/n_s). There was some agreement between the relations obtained to describe the subjective equivalence of noise and vibration at high magnitudes of vibration. However, further work is required to establish the relative importance of railway noise and low magnitudes of vibration produced by the passage of nearby trains.

2.7 A REVIEW OF STUDIES OF THE REACTION TO SIMULTANEOUS NOISE AND VIBRATION: INTERACTION AND COMBINED EFFECTS

2.7.1 Introduction

Since railway noise and railway-induced building vibration very often occur simultaneously, it is desirable to determine whether standards and recommendations for acceptable levels of the two stimuli occurring independently are applicable to a combined stimuli environment. To evaluate disturbance from simultaneous noise and vibration, it is necessary to determine a quantitative measure of the total annoyance caused by noise and vibration from a combination of the annoyance caused by the individual stimuli.

This section reviews studies which have been conducted to investigate the subjective reaction to simultaneous noise and vibration. Some studies were conducted to investigate the influence of the presence of noise on the assessment of vibration and the influence of vibration on the assessment of noise. Other experiments were conducted to determine the total reaction to the two stimuli. The studies are reviewed in chronological order.

2.7.2 Relevant Studies

2.7.2.1 Janssen (1969)

A method of assessing the effect of simultaneous noise and vibration on ships was proposed by Janssen (1969). Experimental data were not reported so it is not known how the relation was derived. The method involved the combination of the individual effects of noise and vibration. A means of assessing the effect of vibration involved the use of K-values (VDI 2057, 1963) which provided a single frequency weighting for application to horizontal and vertical vibration. K-values are based on the highest weighting of the three translational axes at each frequency. However, this method may overestimate the effect of horizontal motion at frequencies greater than 2 Hz while underestimating the effect of low frequency vertical motion. Janssen hypothesised that the effect of simultaneous noise and vibration can be described by:

$$NVR = 10 \log [10^{0.1NR} + 10^{0.1VR}]$$

where NVR is the subjective assessment of simultaneous noise and vibration
NR is the subjective assessment of noise
VR is the subjective assessment of vibration (based on K-values).

But this relation does not appear applicable in the limits: in the absence of noise NR = 0, therefore, from the above relation, NVR = 10 log $(1+10^{0.1VR})$. However, in the absence of noise NVR must be proportional to VR.

The relation is based on the hypothesis that the effects of simultaneous noise and vibration can be described by a logarithmic addition of the individual effects of the two stimuli, in the same manner in which two sound pressure level components are added. The method of assessing simultaneous noise and vibration proposed by Janssen (1969) may be considered unsatisfactory since it was not supported by experimental evidence.

2.7.2.2 Sandover (1970)

A small study, involving four subjects, was conducted by Sandover (1970) to investigate the effect of vibration on equal loudness contours. The subjects matched pure tone noise of frequencies ranging from 125 Hz to 8 kHz with a 125 Hz noise reference stimulus and a 1 kHz noise reference stimulus. The experiment was repeated without the presence of vibration, during exposure to 6 Hz whole-body vertical vibration at 0.12g r.m.s. and also during exposure to 0.37g r.m.s. 25 Hz vertical motion. Vibration was not present during the reference tone. Sandover reported that the presence of vibration at 25 Hz had an effect on the equal loudness contours determined with a noise reference stimulus at 125 Hz. The effect is illustrated in Figure 2.7.1 which is adapted from Sandover (1970). The noise settings were lower when 25 Hz motion was present than when the subject was stationary, suggesting a masking of the noise due to the presence of vibration. No other results were shown, however, Sandover reported little effect of vibration on the equal loudness contours for the other conditions. When the frequencies of the reference tone and the test tone were both 125 Hz, the noise setting of the test stimulus was 30 dB less than the reference stimulus, however, a difference of 0 dB was expected. This large discrepancy suggests there may have been some error in the results.

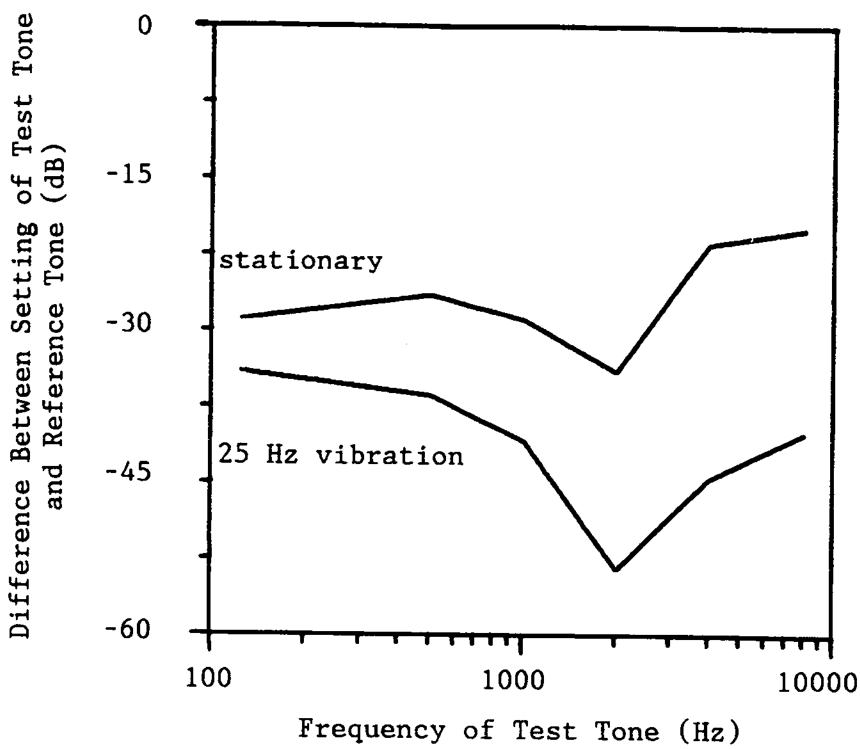

Figure 2.7.1 Equal loudness contours with 125 Hz reference tone. Adapted from Sandover (1970).

2.7.2.3 Grether et al (1971)

A study by Grether et al (1971) sought to determine the effects of combined heat, noise and vibration on human performance, physiological functions and subjective assessment of discomfort. Ten male subjects were presented with five conditions which included a control condition of ambient temperature 72°F, broad band noise at 80 dB and no vibration. Three conditions involved the individual presentation of three stimuli: heat at 120°F, broad band noise at 105 dB and 5 Hz sinusoidal vertical whole-body vibration at 0.3g peak. A combined triple-stress condition was also presented. The duration of each condition was 40 minutes, except for the heat-only condition when the duration was 100 minutes and the triple-stress condition, when the temperature was raised 60 minutes before exposure to all three stimuli. Performance tests were conducted before, during and after each condition. Finally, subjects employed 15 seven-point scales, labelled with different semantic ratings, to provide a subjective assessment of the severity of each session. The mean ratings for the single-stimulus conditions corresponded to greater severity than the mean rating for the control condition. The triple-stimulus condition resulted in the most severe mean rating, however, the differences between the ratings of the five conditions were not significant. The authors provided an explanation of the absence of a difference between the ratings of the conditions by suggesting that the subjects did not fully understand the instructions for the subjective assessment of the stimuli.

2.7.2.4 Innocent and Sandover (1972)

An investigation of the effect of simultaneous noise and vibration on subjective assessment and task performance was conducted by Innocent and Sandover (1972). Thirteen male subjects were presented with all six possible paired combinations of two levels of broad band random noise and three magnitudes of random vertical vibration. First, the method of paired comparisons was employed to determine the relative discomfort of each stimulus. Fifteen pairs of conditions were presented, each of duration 20 seconds. After completion of the paired comparison, the subjects performed tracking and rating tasks. The six combinations of noise and vibration were presented for ten minutes each. A tracking task was performed during the last two minutes, after which an 11-point scale was employed to rate the discomfort caused by each ten-minute session. No experimental data of the subjective assessment of the stimuli were reported but an equation describing a curve fitted to the results obtained from the rating method was provided:

For $N < 72$ dB, $$R = 38.846\ V$$

For $N > 72$ dB, $$R = 0.23\ N + 38.846\ V - 16.538$$

where N is the noise level (dB)

V is the vibration acceleration magnitude (g r.m.s.)

R is the subjective magnitude of discomfort relative to the control condition (72 dB, 0 g r.m.s.).

The equation was used to determine equal comfort contours relating noise and vibration. A linear relationship between subjective magnitude and sound pressure level is implied by the equation. Assuming the subjective magnitude for discomfort of noise may be described by loudness, the equation suggests that a doubling of loudness corresponds to a doubling of the sound pressure level. According to Stevens (1986) a doubling of loudness corresponds to an increase in sound pressure level of 9 dB. Derivation of the equation was not described, so that comment on the usefulness of the relation is limited.

2.7.2.5 *Miwa and Yonekawa (1973)*

A study by Miwa and Yonekawa (1973) was conducted to investigate the interaction of the effects of sound and vibration. The study sought to determine the influence of the presence of noise on the assessment of vibration. Recordings of noise and vibration produced by a diesel pile driver were presented to ten subjects. Fore-and-aft and vertical vibration were presented separately. The vibration consisted of a repeated damped waveform of duration 1.5 seconds and most energy at 10 Hz. Each stimulus was repeated at intervals over a period of 20 seconds. Four experiments were conducted. The first experiment involved adjusting the magnitude of the pile driver vibration, in the presence of four levels of noise, to match the discomfort produced by the same vibration fixed at one magnitude without the presence of noise. The results for vertical and horizontal motion indicated a small increase in the matched vibration magnitude with increasing noise level. This suggests the presence of noise masks the effect of vibration. However, the effect was very small, except at the highest noise level. In the second experiment, the subjects again adjusted the magnitude of pile driver vibration in the presence of noise to match a fixed magnitude of pile driver vibration. In this case, one noise level was presented and the experiment was conducted with five magnitudes of the fixed vibration. Figure 2.7.2 is adapted from Miwa and Yonekawa (1973) and shows the mean magnitude of matched vibration with one standard deviation, for each magnitude of fixed vibration. The results indicated good agreement between the variable vibration and the fixed vibration despite the presence of noise.

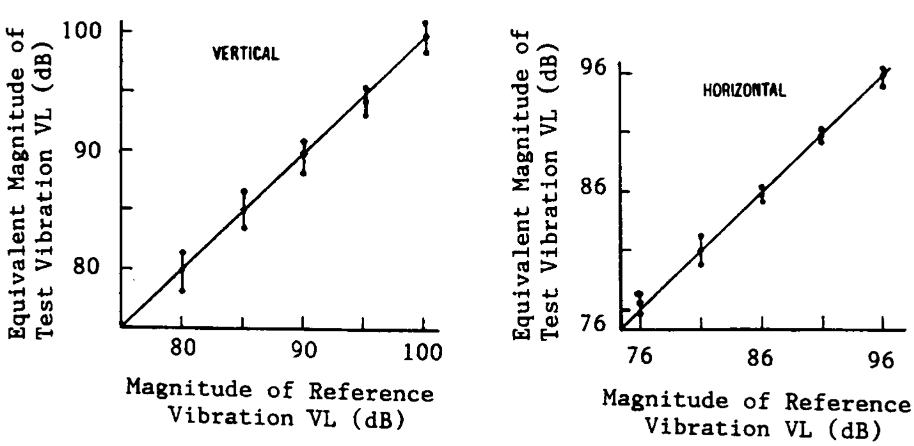

Figure 2.7.2 Subjective matching of vibration in the presence of noise to a reference vibration stimulus.
$VL = 20 \log_{10} a/a_{ref}$ where $a = W_g$ frequency weighted acceleration (ms^{-2} r.m.s.) and $a_{ref} = 10^{-5}\ ms^{-2}$. Adapted from Miwa and Yonekawa (1973).

A third experiment investigated the effect of changing the time interval between the noise and the vibration. Subjects adjusted the magnitude of the vibration stimulus, without the presence of noise, to match a fixed vibration stimulus with noise added at different intervals: simultaneously with the vibration, 0.5 seconds after the vibration, 0.5 seconds before the vibration and 0.7 seconds before the vibration. The magnitude of the variable vibration was about 1.5 dB less than the fixed vibration for all four time intervals. This suggests a masking effect of noise which is independent of the time interval between the noise and the vibration. A further experiment involved matching the pile driver vibration to sinusoidal vibration with noise added at various time intervals. The results indicated some masking effect which was independent of the time interval.

The results from the four experiments suggest that when noise was present during exposure to the fixed vibration, a masking effect occurred whereby the subjective magnitude of vibration was reduced by the presence of noise. The effect was independent of the time interval between the noise and the fixed vibration stimulus. When noise was present during exposure to the variable vibration, no such effect occurred. The conclusions were based on very small changes in the matched vibration magnitude and no statistical analysis was reported.

2.7.2.6 Dempsey, Leatherwood and Drezek (1976)

A study by Dempsey, Leatherwood and Drezek (1976) involved the exposure of 48 subjects to simultaneous noise and vibration. The aim of the study was to investigate the effect of vibration on the assessment of noise, the effect of noise on the assessment of vibration and to determine the overall discomfort from combined noise and vibration. The vibration stimuli consisted of random vertical motion, with a band width of 5 Hz, centred at one of four frequencies: 3, 5, 7 and 9 Hz. Each stimulus was presented at four acceleration magnitudes: 0.03, 0.06, 0.09 and 0.12 g r.m.s. The noise stimuli consisted of octave band random noise centred at frequencies of 250 Hz, 500 Hz, 2 kHz and 4 kHz. The subjects were exposed to four sound pressure levels: 70, 75, 80 and 85 S.P.L. dB(A). All 256 paired combinations of noise and vibration were presented to each subject along with 112 repeated stimuli. A nine point scale was employed to rate each stimulus. There were four parts to the study: the subjects were instructed to rate the noise only, to rate the vibration only, to indicate the discomfort from both the noise and the vibration but separately, on different scales, or to assess the overall discomfort from the combination of noise and vibration. Analysis of variance was conducted to determine which variables had a significant effect on the response.

Figure 2.7.3 is adapted from Dempsey et al (1976) and illustrates the effect of the presence of vibration on the assessment of noise. The figure suggests that vibration had no effect on the assessment of noise, however, analysis of variance indicated a significant effect of vibration. The authors suggested that since the range of vibration magnitudes was small, the significance of the effect of vibration was only of theoretical importance. This interpretation of the results may be considered inconsistent.

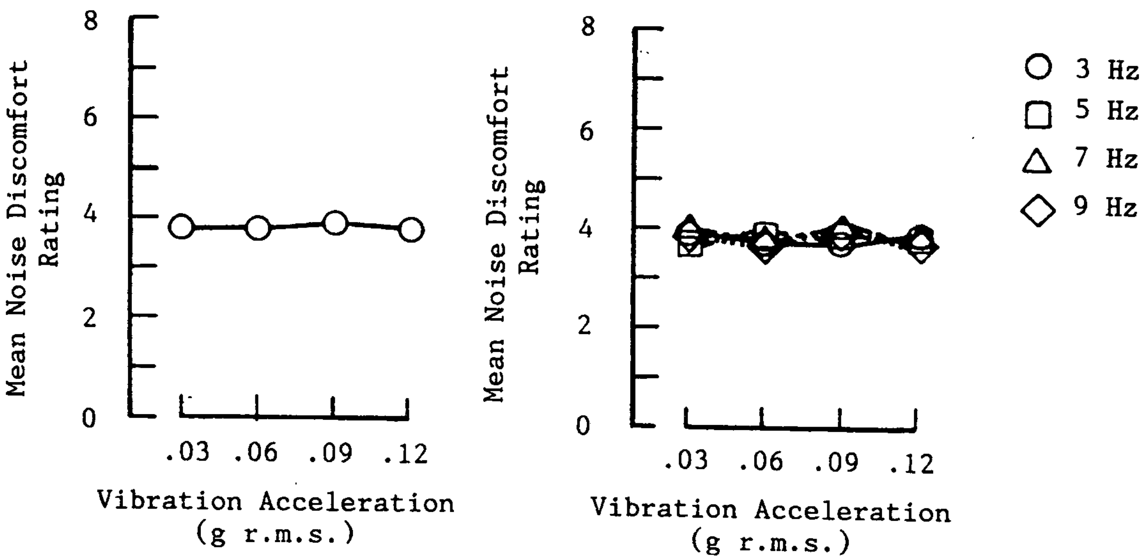

Figure 2.7.3 Assessment of noise in the presence of vibration. Adapted from Dempsey et al (1976).

Figures presented by Dempsey et al illustrating the assessment of vibration in the presence of noise suggested no effect of noise, but analysis of variance conducted on the results of all four parts indicated a significant effect of noise level, frequency of noise, vibration magnitude and vibration frequency and of most combinations of interaction variables. The results from the assessment of noise and vibration separately on different occasions were similar to the results from the separate assessment at the same time. From this the authors concluded that subjects can separate the influence of noise and vibration. The results from rating the stimuli in terms of the overall discomfort showed that the discomfort depends on both stimuli.

This study provides some information on the interaction of the effects of noise and vibration but there appeared to be an anomaly in the interpretation of the results. The study did not provide any quantitative measure of the influence of noise or vibration on the separate or combined assessment of the two stimuli.

2.7.2.7 *Dempsey, Leatherwood and Clevenson (1976, 1979a)*

The investigation described above was continued in a study by Dempsey, Leatherwood and Clevenson (1976) which aimed to determine the interactive effects of noise and vibration on the overall discomfort and to determine a method of quantifying discomfort from simultaneous noise and vibration. Forty-eight seated subjects were exposed to paired combinations of noise and vibration. The sound consisted of octave band random noise centred at 2 kHz or 500 Hz and presented at three sound pressure levels: 75, 85 and 95 dB(A). Sinusoidal and random vertical vibration stimuli were presented. The frequency of motion was 5 Hz with a 5 Hz band width for the random motion. Each vibration stimulus was presented at six acceleration magnitudes. Subjects employed the method of magnitude estimation to assess the overall discomfort from the combination of noise and vibration.

Analysis of variance was conducted on factorial combinations of vibration type (random or sinusoidal), vibration magnitude, noise level and frequency of noise. The results showed that discomfort is a function of all these variables and of double and triple interactions of the variables. The authors concluded that prediction of the combined effect of noise and vibration should not be based on the sum of the individual effects of the two stimuli. However, Dempsey et al then reported that the significance of interaction variables may be an artifact of the existence of different psychophysical measures for noise and vibration from the linear relationship assumed for both stimuli in the analysis of variance. Further analysis was conducted which showed that the interaction variables were not significant if a linear relation was assumed between vibration discomfort, ψ_v, and vibration acceleration, a, i.e. $\psi_v \propto a$, and a power function relationship was applied between noise discomfort, ψ_s, and noise level, (SPL dB(A)), i.e. $\log \psi_s \propto$ SPL. Thus, the authors concluded that the overall discomfort can be predicted from the sum of the individual effects of noise and vibration.

A more detailed version of the study described above was reported later (see Dempsey, Leatherwood, and Clevenson, 1979a). The version provided an equation to describe the discomfort from combined noise and vibration:

$$\text{DISC} = 0.337 + 32.1 \text{ g r.m.s.} + 10^{x}$$

where DISC is the subjective response to the combined stimuli

$x = -41.9 \text{ g r.m.s.} - 3.16 + (0.0378 + 0.395 \text{ g r.m.s.})\, L_D$

g r.m.s. = overall r.m.s. acceleration

L_D = S.P.L. dB(D)

The derivation of this relation was not described. The authors explained the first two terms (0.337 + 32.1g r.m.s.) as the contribution of vibration to the total discomfort. The third term was described as noise discomfort contribution. It is not clear why vibration acceleration is present in the third term despite the insignificance of the interaction variables when a linear relationship was applied between discomfort and vibration and a power relationship applied for noise.

2.7.2.8 Kirby et al (1977)

The effects of whole-body vibration and simultaneous noise on the subjective evaluation of ride quality was investigated by Kirby et al (1977). Twelve seated women were presented with vertical sinusoidal vibration combined with broad band noise centred at 500 Hz. The subjects were exposed to all possible combinations of two levels of noise (60 dB(A) and 85 dB(A) SPL) paired with three magnitudes of vertical vibration (0.05, 0.15 and 0.25g peak) at each of four frequencies (2, 5, 9 and 15 Hz). The stimuli were divided into groups of eight. Before each group, two stimuli were presented to provide an example of a "low-number stimulus" and a "high-number stimulus." A nine point rating scale was employed to indicate the discomfort caused by each combination of noise and vibration.

Analysis of variance was performed on the results to determine the significance of the effect of vibration frequency, vibration magnitude, noise level and factorial combinations of these variables. There was a significant effect of each variable and of the interaction variable involving vibration magnitude, vibration frequency and noise level. Unlike Dempsey, Leatherwood and Clevenson (1976), analysis with power functions was not conducted. Figure 2.7.4 is adapted from Kirby et al (1977) and illustrates the effect of noise on the overall discomfort, averaging over the four frequencies. The figure indicates that the presence of noise provided a larger contribution to the discomfort at low magnitudes of vibration than at high magnitudes. However, the authors suggested that the reduction in the effect of noise may be due to the end effect of the scale. No quantitative measure of the combined effect of noise and vibration was determined.

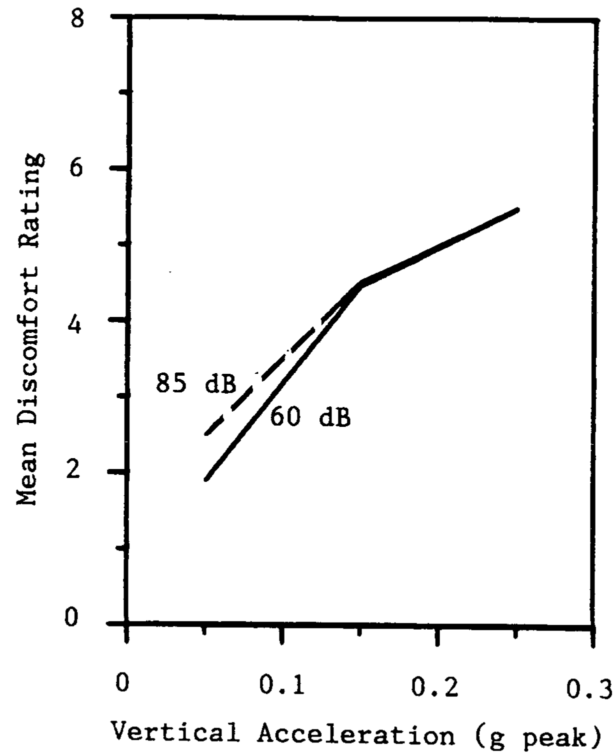

Figure 2.7.4 Subjective rating as a function of vertical acceleration for two noise levels. Adapted from Kirby et al (1977).

2.7.2.9 Leatherwood (1979)

A study was conducted by Leatherwood (1979) in which a numerical model was determined to evaluate the discomfort produced by combined noise and vibration. Sixty subjects participated in an experiment which employed the method of magnitude estimation. The study sought to determine the effects of four independent variables: A-weighted noise level, frequency of noise, "vibration discomfort level" and vibration frequency. The "vibration discomfort level" was based on predetermined linear relations between subjective response and acceleration magnitude at each frequency of vibration. The ratio scale of discomfort determined at each frequency of vertical vibration was adjusted to have a value of unity at the discomfort threshold in order to produce a scale of discomfort which was independent of frequency. Leatherwood suggested that the use of the scale of "vibration discomfort level" as an independent variable allows for the effect of vibration frequency and therefore permitted focus in this study on the incremental discomfort due to the presence of noise. A table was provided giving the coefficients of the regression analysis relating subjective response and acceleration magnitude at each frequency of motion. The coefficients were determined in two previous studies: Leatherwood and Dempsey (1976b) and Dempsey and Leatherwood

(1976).

The subjects were exposed to stimuli consisting of simultaneous noise and vertical vibration. All combinations of four levels of noise (dB(A)), four frequencies of noise, four "vibration discomfort levels" and four vibration frequencies were presented. The reference stimuli consisted of vibration only and were assigned the value of 100. The subjects were instructed to assign numbers according to the total discomfort due to noise and vibration.

A four factor analysis of variance and post hoc multiple comparison procedure were conducted to determine the significance of each of the four independent variables and all interactions of these variables. The author reported that analysis of the results showed that the "vibration discomfort level" was successful in accounting for the effect of frequency. This conclusion was based on the results of the post hoc multiple comparison procedure for which the effect of frequency was not significant. However, the selected level of significance was very small ($p = 0.005$). Analysis of variance indicated a significant effect of frequency ($p = 0.05$) which suggests the "vibration discomfort level" was not successful in allowing for the effect of frequency. Leatherwood explained the use of a more stringent level of significance in the multiple comparison procedure by suggesting that statistical significance did not necessarily imply practical significance. It may be appropriate to consider this explanation with some caution.

Analysis of the results suggested a significant effect of noise frequency despite the use of A-weighted noise levels. The results also indicate that the effect of the frequency of A-weighted noise depends on the noise level, with the effect of lowest and highest frequencies (63 Hz and 2 kHz), increasing with level. However, other studies have indicated little change in the shape of the frequency weightings with increasing noise level, except at low frequencies when the weightings decreased with increasing noise level (see Robinson and Dadson, 1971), an opposite effect to that indicated by Leatherwood (1979).

A four-step method of evaluating the discomfort due to simultaneous noise and vibration was determined from the results of the study. The method made the assumption that the overall discomfort was equal to the sum of the discomfort due to vibration and the incremental discomfort due to noise in the presence of vibration. First the discomfort produced by the vibration was calculated in units of "vibration discomfort level" from a previously determined equation allowing for the effect of vibration frequency (see Dempsey, Leatherwood and Clevenson, 1979b).

Then the incremental discomfort due to noise was calculated from an equation determined from the regression analysis of results from the present study. A weighting was applied to allow for the effect of the frequency of the noise and finally the sum of the discomfort from the two stimuli was calculated.

The main source of inaccuracy in this method probably arises from the use of the "vibration discomfort level" which was unlikely to have correctly accounted for the effect of vibration frequency. Other uncertainties arise from the frequency weightings for noise and the interpretation of the results of the statistical analysis.

2.7.2.10 Irwin (1983, 1985)

A method for the assessment of human response to combined noise and vibration was presented by Irwin (1983, 1985). The method involves the summation of components of horizontal and vertical acceleration, yaw acceleration and a noise component, to give the "Combined Environmental Parameter". The latter involves the noise level, the frequency of the noise and the frequency of the vibration stimuli. Multiplying factors were indicated for impulsive events. A series of curves were provided corresponding to the Combined Environmental Parameter as a function of the mean frequency of the translational and yaw vibration, to indicate levels of perception and acceptability.

The experimental results from which the method was derived were not provided. Irwin did not explain the notions on which the method was based, therefore comment on the method is restricted.

2.7.2.11 Leatherwood, Clevenson and Hollenbaugh (1984)

The relation derived by Leatherwood (1979) to evaluate discomfort produced by noise and vibration was tested in an experiment conducted by Leatherwood, Clevenson and Hollenbaugh (1984). Subjects employed a nine point scale to rate the discomfort from simulations of noise and vertical vibration produced by five different types of helicopter. For each type of helicopter simulation subjects were exposed to four levels of noise and three acceleration magnitudes of vibration. The mean discomfort rating as a function of acceleration magnitude was shown for each noise level and helicopter type. The figure suggests that an increase in acceleration magnitude has less effect on the discomfort at high noise levels than at low noise levels and an increase in noise level has less effect on discomfort at high vibration magnitudes than at low vibration magnitudes. The authors suggested that this illustrates the presence of interaction effects between noise and vibration. However, the result may have been an artifact of the end effect of the scale.

The mean discomfort rating was correlated with unweighted vibration acceleration, weighted acceleration (using the weighting determined by Leatherwood and Dempsey, 1976b), A-weighted noise level and the predicted discomfort from the relation obtained by Leatherwood (1979). The correlation coefficient was largest when the discomfort was correlated with the predicted discomfort. However, the correlation was based on a second-order polynomial fit while a correlation coefficient of unity for a first order relation would indicate a perfect prediction.

Figure 2.7.5 is adapted from Leatherwood et al (1984) and shows the mean discomfort as a function of the predicted response. The authors justified the use of the second order polynomial as allowing for the end effect of the nine-point scale. However, the need for the second order equation may have been a result of the inaccuracy of predicted values.

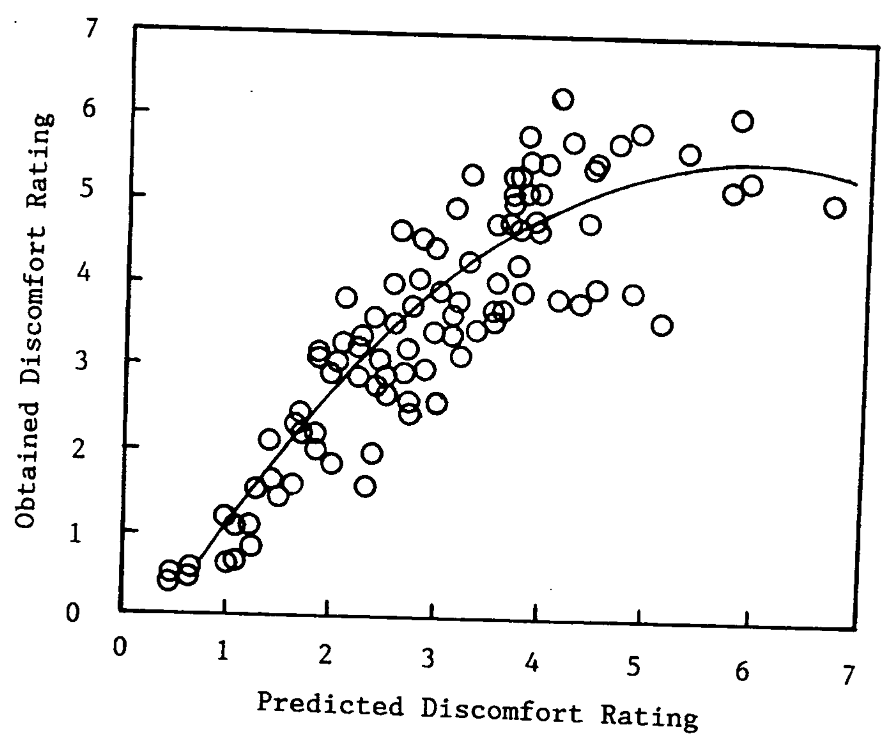

Figure 2.7.5 Relationship between obtained discomfort ratings and predicted discomfort ratings. Adapted from Leatherwood et al (1984).

2.7.3 Discussion and Conclusions

The studies reviewed were conducted to investigate several aspects of response to noise and vibration. Three studies reported the influence of the presence of one stimulus on the assessment of the other. Nine studies involved the overall response to simultaneous noise and vibration. Of these, seven proposed or tested a relation to predict the combined effects of the two stimuli.

Sandover (1970) investigated the effect of the presence of vibration on equal loudness contours for pure tones from 125 Hz to 8 kHz. Influence of the presence of vibration was detected for 125 Hz noise alone. Miwa and Yonekawa (1973) sought to determine the influence of the presence of noise on the assessment of vibration. Subjective matching was conducted which indicated that when noise was present during exposure to vibration, reaction to the vibration was reduced. Dempsey, Leatherwood and Drezek (1976) investigated the effect of noise on the assessment of vibration, and the effect of vibration on the assessment of noise. Analysis of variance indicated a significant effect in both cases. These three studies provide some evidence of an influence of the presence of one stimulus on the assessment of the other stimulus.

Grether et al (1971) investigated response to combined heat, noise and vibration. Mean ratings for the single-stimulus conditions were greater than the control conditions. The triple-stimulus condition resulted in the highest ratings. However, there was no significant difference between any of the conditions. Dempsey, Leatherwood and Drezek (1976) reported that response to combined noise and vibration indicated that subjective reaction depended on both stimuli. Kirby et al (1977) reported significant interactions between the effects of noise and vibration. Application of these findings are limited since no quantitative measure of assessing combined noise and vibration was derived in the studies conducted by Grether et al, Dempsey et al and Kirby et al.

A method of assessing the effect of simultaneous noise and vibration was proposed by Janssen (1969). The method added the effect of the individual stimuli in a manner similar to adding two noise components. The method of deriving the relation was not described. Innocent and Sandover (1972) derived an expression from experimental data to describe the response to simultaneous noise and vibration. However, the expression implied the improbability of a linear relation between discomfort and sound pressure level. Dempsey, Leatherwood and Clevenson (1976, 1979a) reported no significant interaction between the effects of noise and vibration. An expression for the combined effects of the two stimuli was proposed but it is not clear how the relation originated. Leatherwood (1979) derived a method of evaluating the combined effects of noise and vibration. Several uncertainties about the method arise from the use of the unit "vibration discomfort level" and from the frequency weightings for noise. Irwin (1983, 1985) described a method of evaluating combined noise and vibration but the derivation of the method was not described.

The section has shown that there is some information on the influence of noise on the assessment of vibration and on the influence of vibration on the assessment of noise, however, the investigations are few and the results are not all in agreement. Of the studies conducted to investigate the combined effects of noise and vibration, only two fully described the derivation of a relation to predict the effects of the combined stimuli. It is apparent that some discretion may be appropriate when applying these methods. It is clear that further work is necessary to quantify the interaction and combined effects of noise and vibration.

2.8 GENERAL CONCLUSIONS OF LITERATURE REVIEW

This review of previous studies has shown that there are several areas in which there is inadequate information to provide an exhaustive procedure for evaluating building vibration produced by the passage of nearby trains.

Although there have been many investigations of the growth function of the subjective magnitude of vibration as a function of the objective magnitude, most of the studies involved vibration magnitudes much greater than the magnitudes to which residents may be exposed during the passage of trains. Further investigations are required to determine the growth function at vibration magnitudes near the perception threshold.

The studies reviewed have shown that there is much evidence to indicate that a time dependency defined by an exponent of 2 relating acceleration magnitude, a, and duration, t, ($a^2t = k$) overestimates the effect of duration on subjective response to vibration. An exponent substantially greater than 2 appears to be more appropriate, however, further investigations are necessary to establish the value of the exponent when describing the time dependency of response to intermittent vibration, such as produced by trains.

A comparison of the findings of previous experiments conducted to determine perception thresholds and comfort contours in the same study shows little agreement. It is not possible to determine from the experimental data currently available whether the frequency dependence of reaction to high magnitude vibration is the same as the frequency dependence of reaction to low magnitude vibration or of perception thresholds. Further work is required to determine frequency weightings for low magnitude vibration which can be applied to railway-induced building vibration.

A small number of studies have been conducted to investigate the subjective equivalence of noise and vibration. There was some agreement between the results of the studies, however, with the exception of one study, the experiments involved vibration at high magnitudes. Investigations are necessary to determine the relative importance of noise and vibration at low magnitudes.

Only a small number of studies have been conducted to determine the influence of noise on the assessment of vibration and the influence of vibration on the assessment of noise and the results are not all in agreement. More data is needed on the interaction of the effects of noise and vibration. Further work is also required to determine a method of predicting the combined effects of noise and vibration since previous work in this area has been shown to be inadequate.

A programme of research is required which will provide data on which to base an exhaustive procedure for evaluating railway-induced building vibration. The areas of research considered necessary are as follows:

1) The effect on annoyance of number of trains and magnitude of vibration.

2) Determination of the trade-off between number of trains and magnitude of vibration.

3) The relative importance of noise and vibration from railways.

4) The interaction and combined effects of noise and vibration from railways.

5) The frequency dependence of subjective reaction to vertical and horizontal whole-body vibration at low magnitudes.

6) Prediction of the relative annoyance from exposure to complex conditions of combined noise and railway-induced building vibration.

CHAPTER 3

LABORATORY APPARATUS AND STIMULI GENERATION

3.1 INTRODUCTION

A series of laboratory experiments were conducted which are described in full in Chapters 4 to 7. The experiments involved the exposure of men and women to vibration and noise. This chapter provides details of the apparatus employed in the experiments and the procedures used to generate the stimuli. Section 3.2 is concerned with the apparatus and generation of the stimuli employed in Experiments 1, 2, 3, 4 and 6. These experiments involved presentation of vertical vibration and noise or vertical vibration alone. Section 3.3 is concerned with the apparatus and generation of the stimuli employed in Experiment 5 which involved presentation of vertical and horizontal vibration and a noise stimulus.

3.2 APPARATUS AND GENERATION OF STIMULI FOR EXPERIMENTS 1, 2, 3, 4 AND 6

3.2.1 Experimental Chamber

Experiments 1, 2, 3, 4 and 6 took place in a room which was fitted with a carpet, curtains and a wall-mounted picture to provide a reasonable representation of a small, comfortable sitting-room. The ceiling and walls were soundproofed to avoid any effect of extraneous noise. The subjects sat on a seat driven by a vibrator in the centre of the room. The experiment was controlled from an adjoining room, from where the experimenter communicated with the subject by use of a two-way intercom.

3.2.2 Apparatus for Vibration Generation

The vibration stimuli presented in Experiments 1, 2, 3, 4 and 6 were generated by a Derritron VP30 electromagnetic vibrator which was powered by a 300 watt amplifier. The vibrator was surrounded by a metal box frame. Four springs were attached from the frame to the underside of an aluminium plate which was connected to the vibrator table. One spring was attached to each corner of the plate. The springs supported the weight of the subject. Movement of the vibrator table was constrained to the vertical (z-axis) only by eight steel flexures attached from the frame to the aluminium plate. A schematic diagram of the vibrator and frame is shown in Figure 3.1.

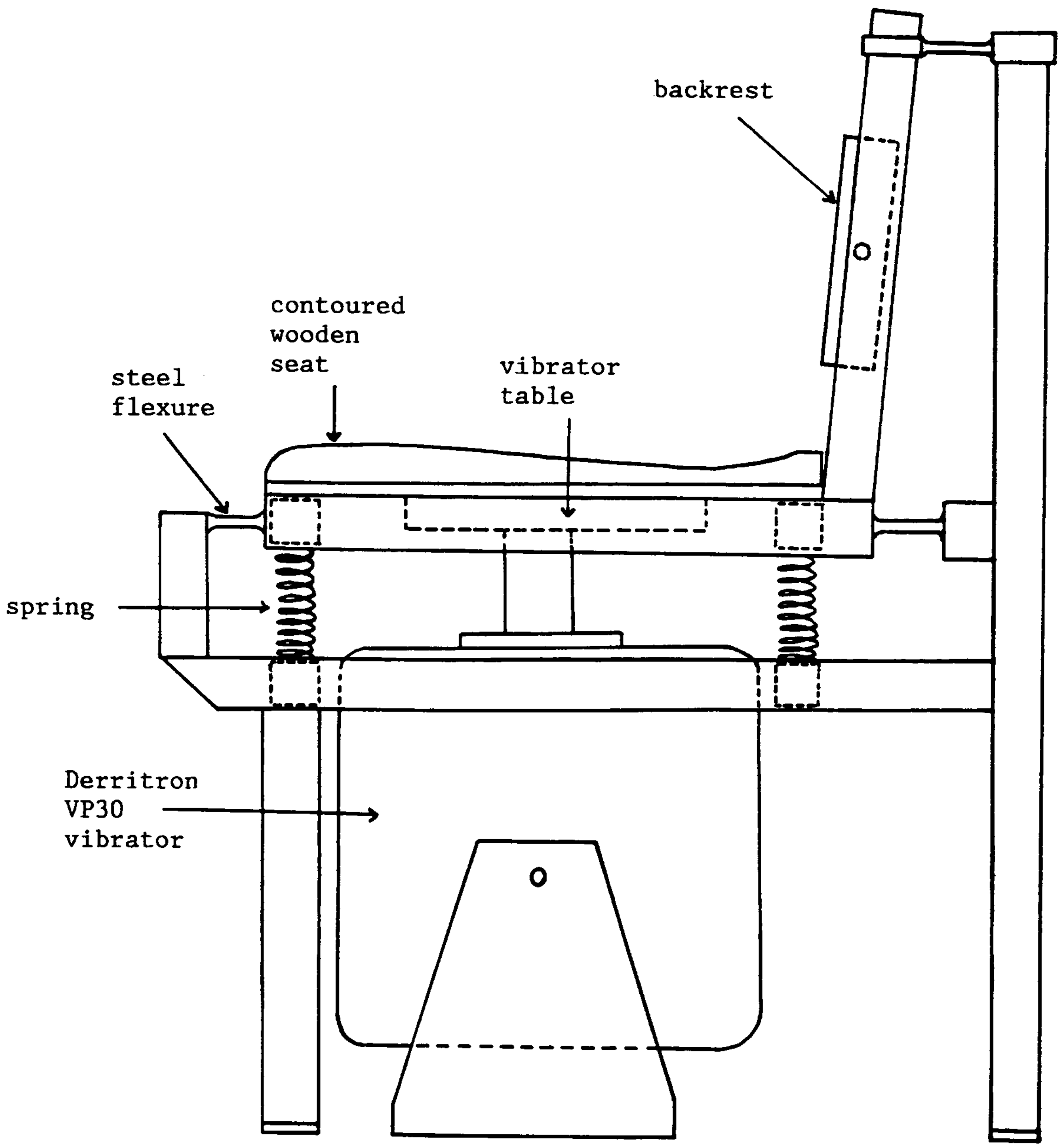

Figure 3.1 Schematic diagram of the VP30 vibrator and frame employed in Experiments 1, 2, 3, 4 and 6.

The subjects sat on a rigid wooden seat which was attached to the aluminium plate. The seat was contoured to provide greater comfort than a flat seat by distributing the weight of the subject around a larger area, reducing pressure on the ischial tuberosities. A stationary wooden backrest which was slightly contoured for comfort was attached to the box frame. Figure 3.2 provides schematic diagrams of the seat and backrest.

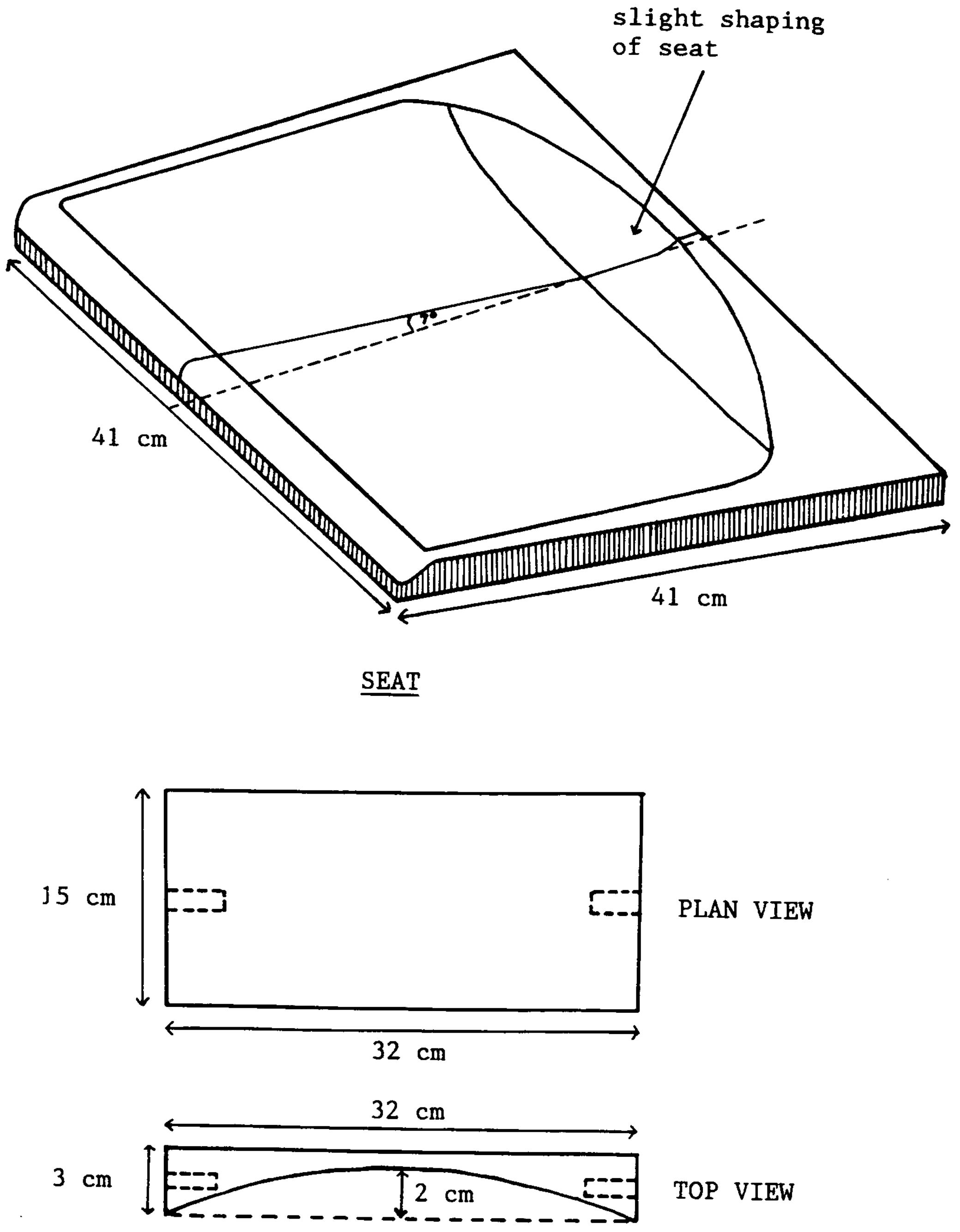

Figure 3.2 Schematic diagrams of the contoured wooden seat and backrest.

The subjects' feet rested on a flat, stationary footrest which was adjusted in height to position the thighs horizontally and the lower legs vertically. A layer of sponge was place between the feet and footrest during Experiments 3, 4 and 6 to isolate the feet from noise-induced vibration of the footrest. Photographs of the apparatus taken from two angles are shown in Figures 3.3 and 3.4.

Vertical acceleration of the vibrator was measured using a Schaevitz A220-0002 accelerometer. The accelerometer was mounted underneath the seat, on the supporting column between the vibrator and the vibrator table.

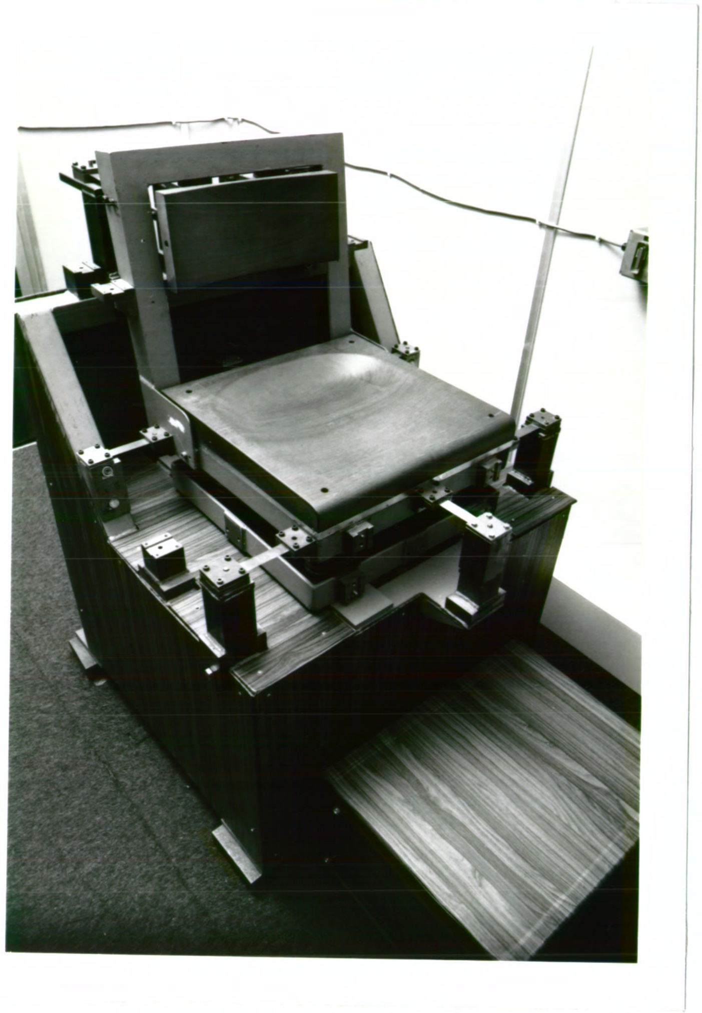

Figure 3.3 Front view of the apparatus for vibration generation employed in Experiments 1, 2, 3, 4 and 6.

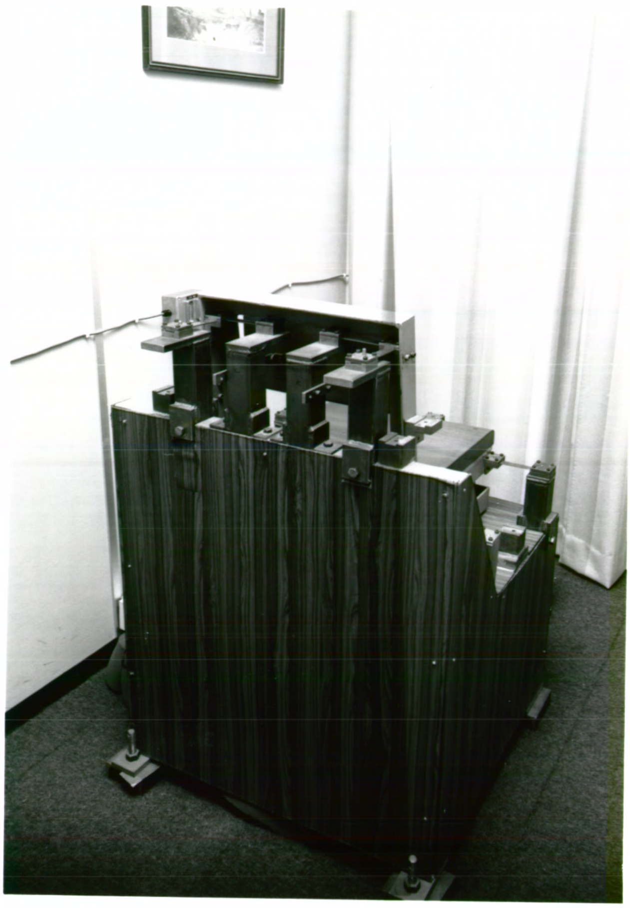

Figure 3.4 Back view of the apparatus for vibration generation employed in Experiments 1, 2, 3, 4 and 6.

3.2.3 Generation of Vibration Stimuli

The acceleration time histories of the vibration stimuli presented in Experiments 1, 2, 3, 4 and 6 were frequency weighted to compensate for the response of the vibrator–subject combination. This involved determination of the frequency response function, H(f). The vibrator–subject combination was assumed to respond as a single input–single output linear system. Figure 3.5 provides a representation of the system, where x(t) and y(t) are the input and output respectively in the time domain and h(t) is the response of a linear time invariant system to a unit impulse (impulse response function).

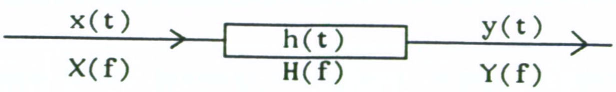

Figure 3.5 Representation of a single input–single output linear system.

With a subject seated on the vibrator, the acceleration output response was measured with a constant amplitude swept sinusoidal input consisting of frequencies in the range 1 Hz to 100 Hz. The frequency response function of the vibrator–subject combination, H(f), was determined from the ratio of the Fourier transforms of the output to the input,

i.e.
$$H(f) = \frac{Y(f)}{X(f)}$$

where
$$H(f) = \int_{-\infty}^{\infty} h(t)\, e^{-j2\pi ft}\, dt$$

$$Y(f) = \int_{-\infty}^{\infty} y(t)\, e^{-j2\pi ft}\, dt$$

$$X(f) = \int_{-\infty}^{\infty} x(t)\, e^{-j2\pi ft}\, dt$$

Figure 3.6 shows the frequency response function of the vibrator–subject combination.

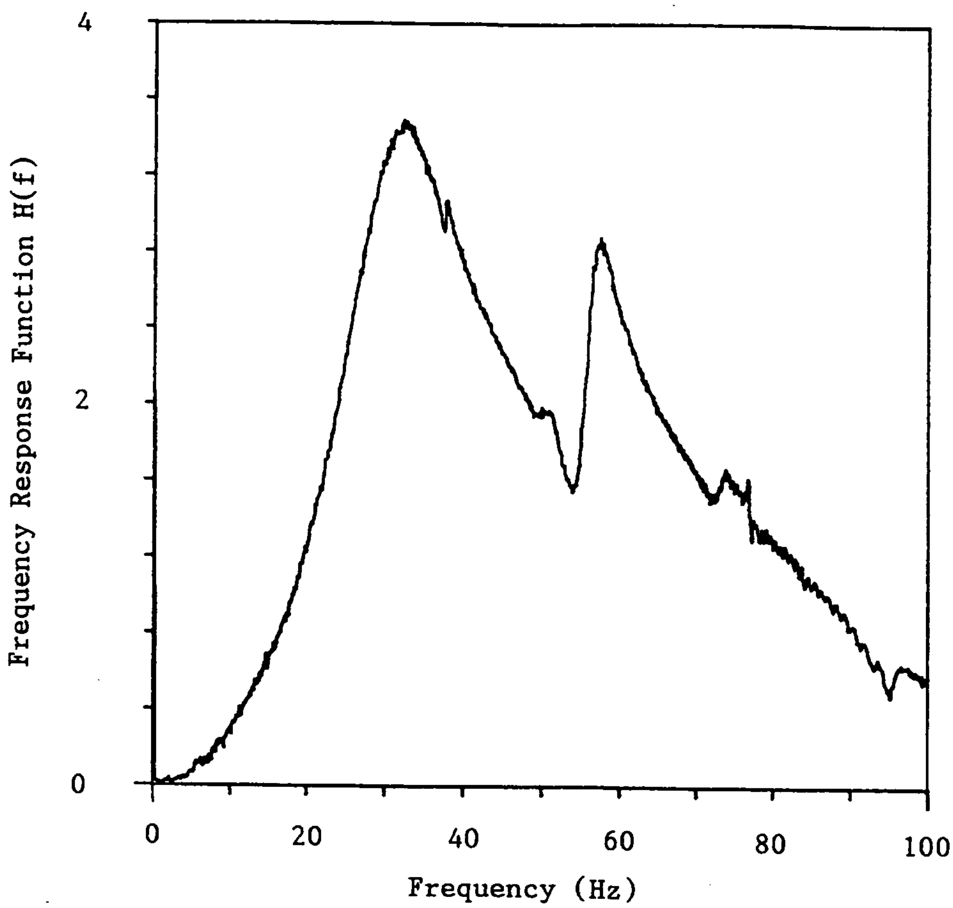

Figure 3.6 Frequency response function of the Derritron VP30 electromagnetic vibrator.

The acceleration time histories, a(t), were frequency weighted by multiplication of the Fourier transform of the time history, A(f), and the inverse of the frequency response function, 1/H(f). The frequency weighted acceleration time histories, b(t), were then obtained by conducting an inverse Fourier transform,

i.e.

$$B(f) = \frac{A(f)}{H(f)}$$

$$b(t) = \int_{-\infty}^{\infty} B(f)\, e^{j2\pi ft}\, df$$

A PDP 11/34 computer was employed to compute the transfer function of the vibrator, to generate the frequency weighted vibration stimuli and to analyse the results of the experiments. During the experiments the frequency weighted time histories, b(t), were used as the input to the vibrator amplifier via a 10 bit digital–to–analogue converter and an eight pole Butterworth low pass filter. For Experiments 3 and 4 the vibration stimuli were recorded onto cassette tapes using a TEAC R70–A four channel tape–recorder and replayed during the experiments.

3.2.3.1 Intersubject Variability, Cross–axis Coupling and Background Vibration

Figures 3.7, 3.8 and 3.9 show power spectral densities for acceleration recorded on the seat when the same frequency weighted vibration stimulus was presented to six, four and three subjects respectively. Figure 3.7 shows the vibration stimulus presented in Experiments 1 and 2; Figure 3.8 shows the vibration stimulus presented in Experiments 3 and 4; Figure 3.9 shows the vibration stimuli presented in Experiment 6. The variability in the magnitude of each stimulus experienced by each subject in Experiments 1, 2, 3 and 4 was no more than ±4% of the mean root–mean–square acceleration averaged over the duration of the stimulus. In Experiment 6, the average standard deviation of the acceleration magnitudes of each stimulus presented was about 10% of the mean magnitude. The cross–axis coupling, as a measure of the difference in the vertical acceleration between the ischial tuberosities, was no more than ±2% of the acceleration in the centre, between them. The background vibration was no greater than 0.005 ms^{-2} r.m.s., with most energy at 50 Hz and 100 Hz. This magnitude of vibration is not perceptible.

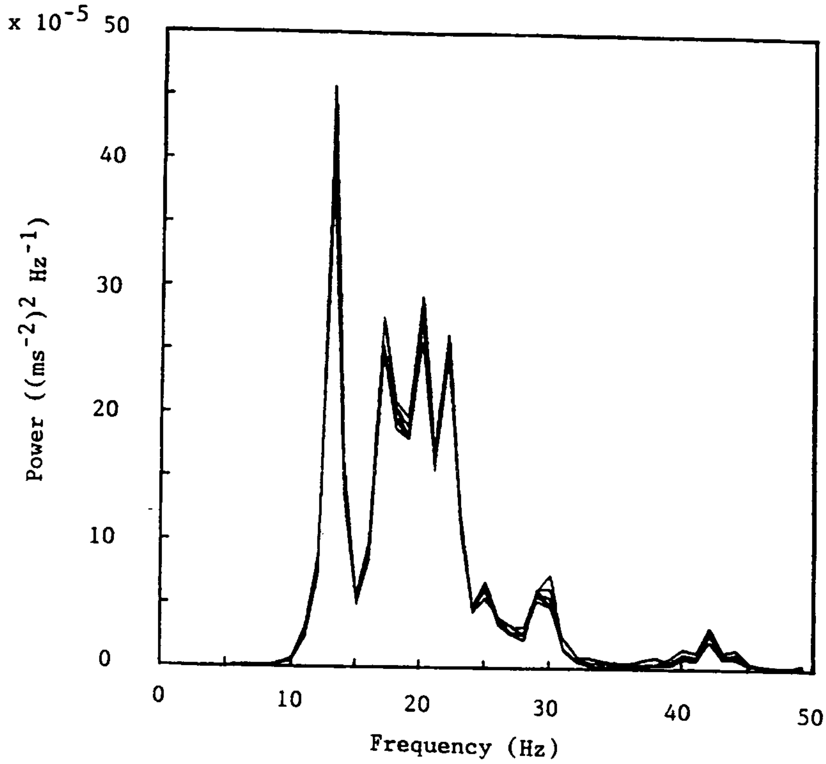

Figure 3.7 Power spectral densities for the vibration stimulus experienced by six subjects in Experiments 1 and 2 (resolution 1 Hz, degrees of freedom 48).

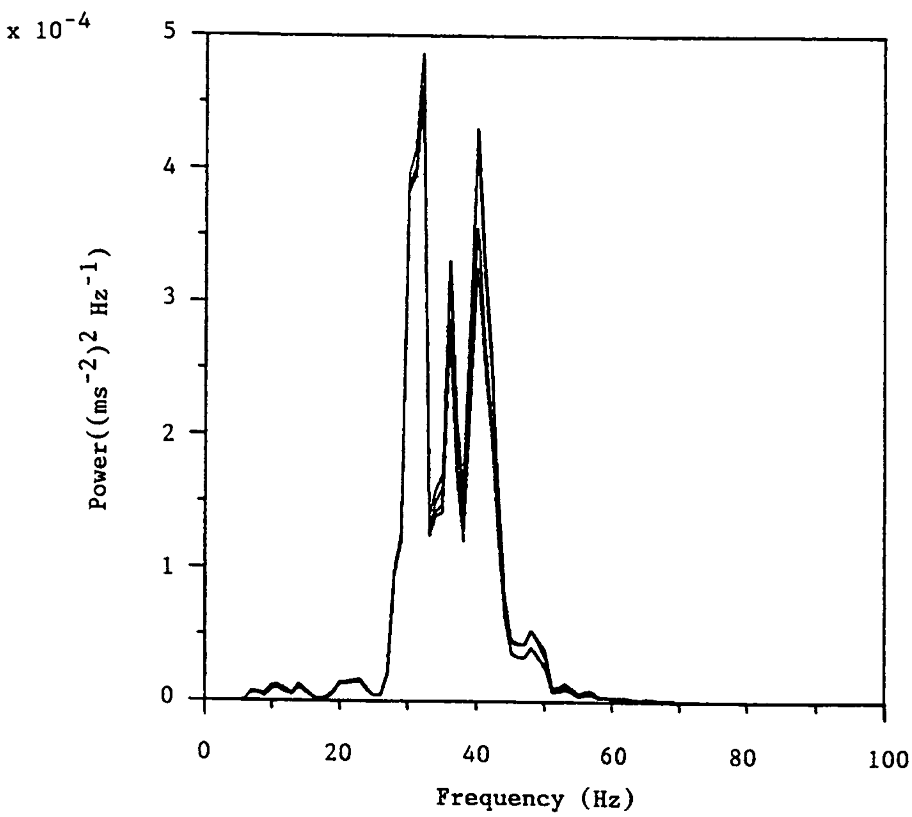

Figure 3.8 Power spectral densities for one magnitude of the vibration stimulus experienced by four subjects in Experiments 3 and 4 (VDV = 0.10 $ms^{-1.75}$, resolution 1 Hz, degrees of freedom 94).

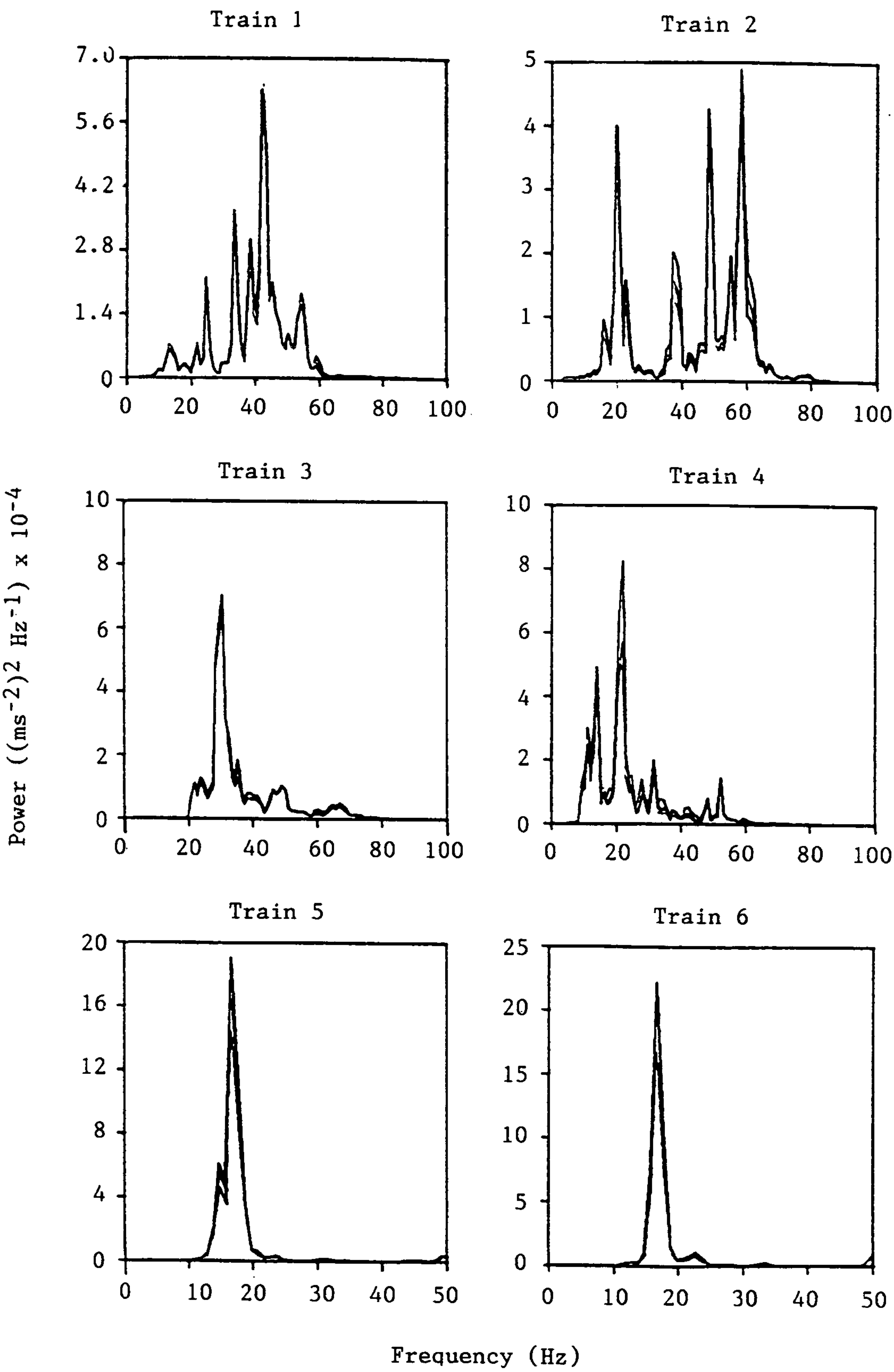

Figure 3.9 Power spectral densities for one magnitude of each vibration stimulus experienced by three subjects in Experiment 6 (resolution 1 Hz).

3.2.4 Apparatus for Noise Generation

In Experiments 3 and 4, the noise stimuli were transferred onto cassette tapes in synchronisation with the vibration stimuli and replayed during the experiments. For this purpose a TEAC R70-A four channel tape-recorder and a DBX noise reduction system were employed. The noise stimuli were generated by two 100 watt Tannoy Mercury loudspeakers via a Technics SU-V4X amplifier and DBX noise reduction system. The loudspeakers were situated behind a curtain in front of the subject.

3.2.5 Generation of Noise Stimuli

The frequency response of the apparatus was determined in the room in which the experiments took place. A pink noise input at a sound pressure level of 75 dB(A) was employed. (Pink noise consists of a continuous random spectrum which has equal power in constant percentage bandwidths (e.g. octave bands) over a specified frequency range.) The frequency response was found to be reasonably flat between 50 Hz and 8 kHz (Figure 3.10).

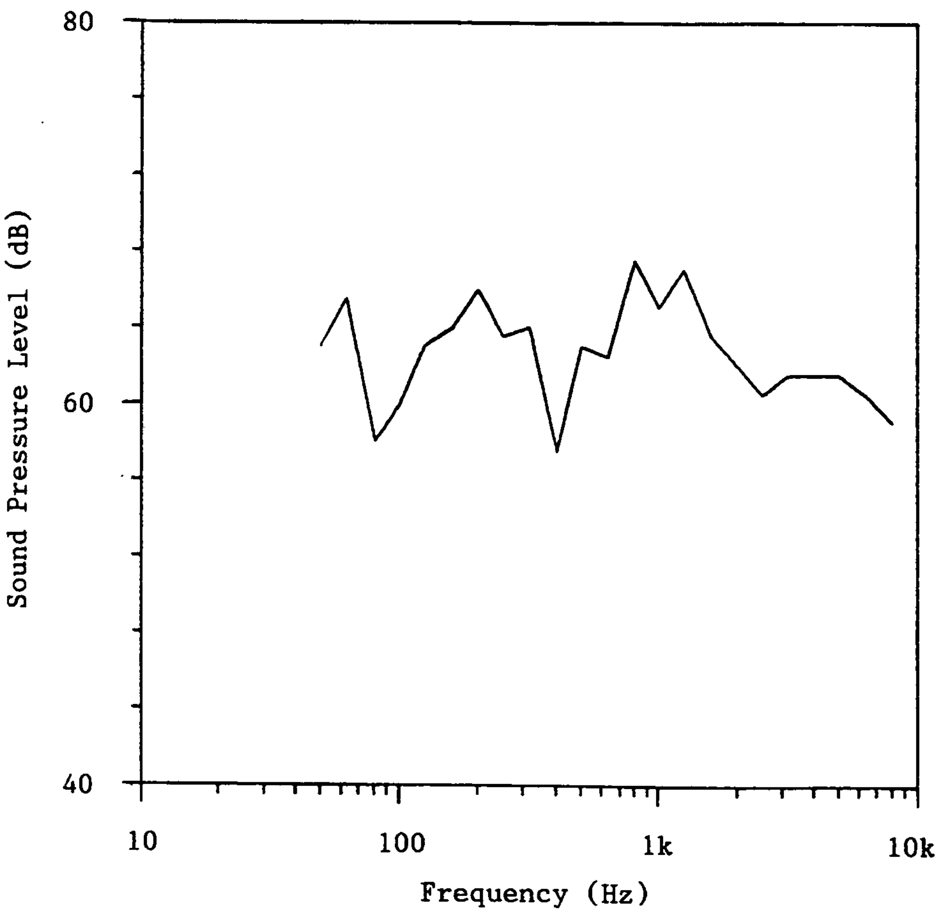

Figure 3.10 Frequency response of the noise apparatus.

A Bruel and Kjaer digital frequency analyser Type 2131 was employed using linear averaging to determine a $^1/_3$-octave spectrum of the original noise recording which was reproduced in Experiments 3 and 4. This was compared with the $^1/_3$-octave spectrum of the noise reproduced in the laboratory. The tone controls on the amplifier were adjusted so that the spectrum of the noise stimulus at the position of the subject's head was within 2 dB of the level of the original recording at each of the $^1/_3$-octaves in the frequency range 100 Hz to 5 kHz. Figure 3.11 shows the spectrum of the original noise recording and the spectrum of the noise reproduced in the laboratory.

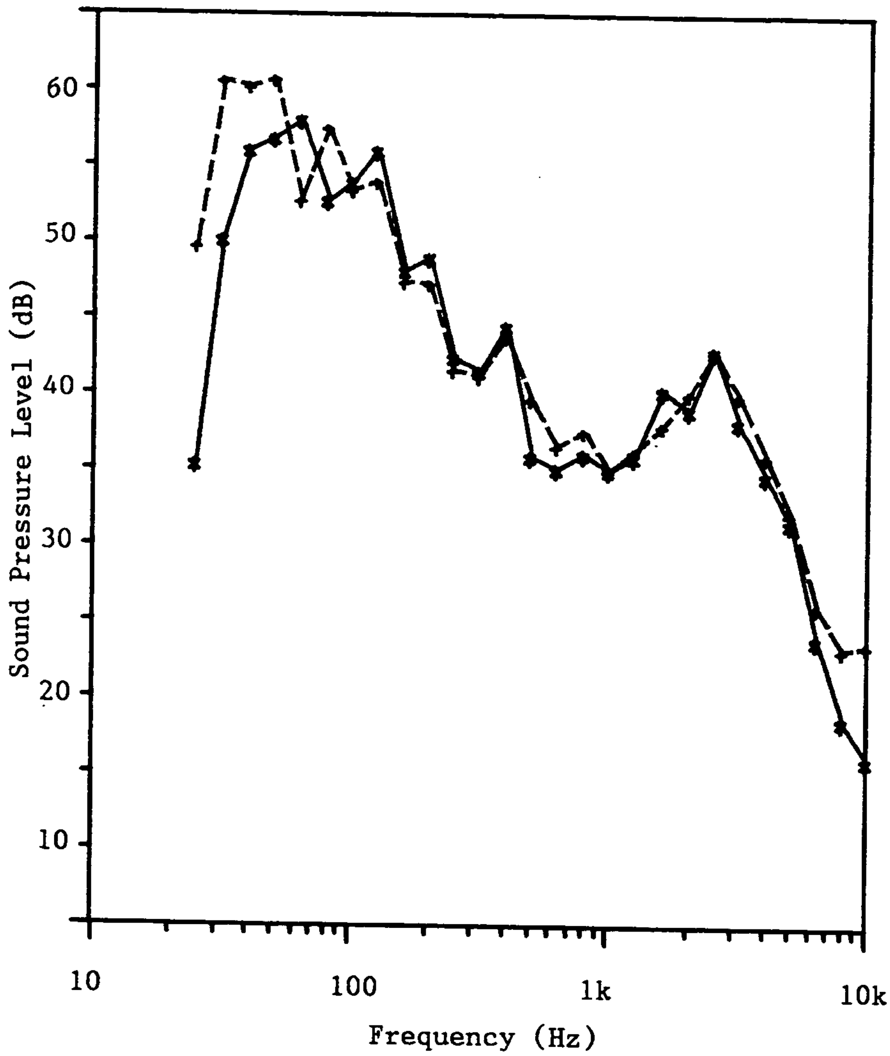

Figure 3.11 Comparison of spectra of original (---) and reproduced (——) noise stimuli presented in Experiments 3 and 4.

A Bruel and Kjaer sound level meter Type 2218 was employed to measure the sound exposure level of the noise stimuli. The background noise level at the position of the subject's head was broad band at a sound pressure level of 42 dB(A) and was primarily due to the cooling system of the vibrator.

3.3 APPARATUS AND GENERATION OF STIMULI FOR EXPERIMENT 5

3.3.1 Apparatus for Vibration Generation

3.3.1.1 Apparatus for Generation of Vertical (z-axis) Vibration

For Experiment 5, vertical (z-axis) whole-body vibration was produced by a one-metre stroke vertical hydraulic vibrator. The vertical vibration simulator system has a 10 kN dynamic force. It can operate over a wide frequency range and at acceleration magnitudes up to 10 ms^{-2}. Figure 3.12 provides a schematic diagram of the vibrator system. A servo-hydraulic actuator cylinder was mounted vertically within a support flange on a concrete block. Four supporting struts, also mounted in the concrete block, were attached to the top of the actuator cylinder. A vibrator table, which was fitted with an anti-rotation assembly, was fixed to the end of the piston rod. The use of a hydrostatic piston and bearings and the elimination of oil seals on the cylinder facilitated generation of waveforms of low distortion. Hydraulic power to the actuator was supplied by a Power Pack.

The subjects sat on a rigid wooden seat which was attached directly to one side of the platform. The seat was contoured to provide greater comfort than a flat seat. Figure 3.2 provides a schematic diagram of the seat. The feet and thighs of the subjects were positioned horizontally and the lower legs vertically by means of an adjustable, stationary footrest placed beside the platform. There was no backrest.

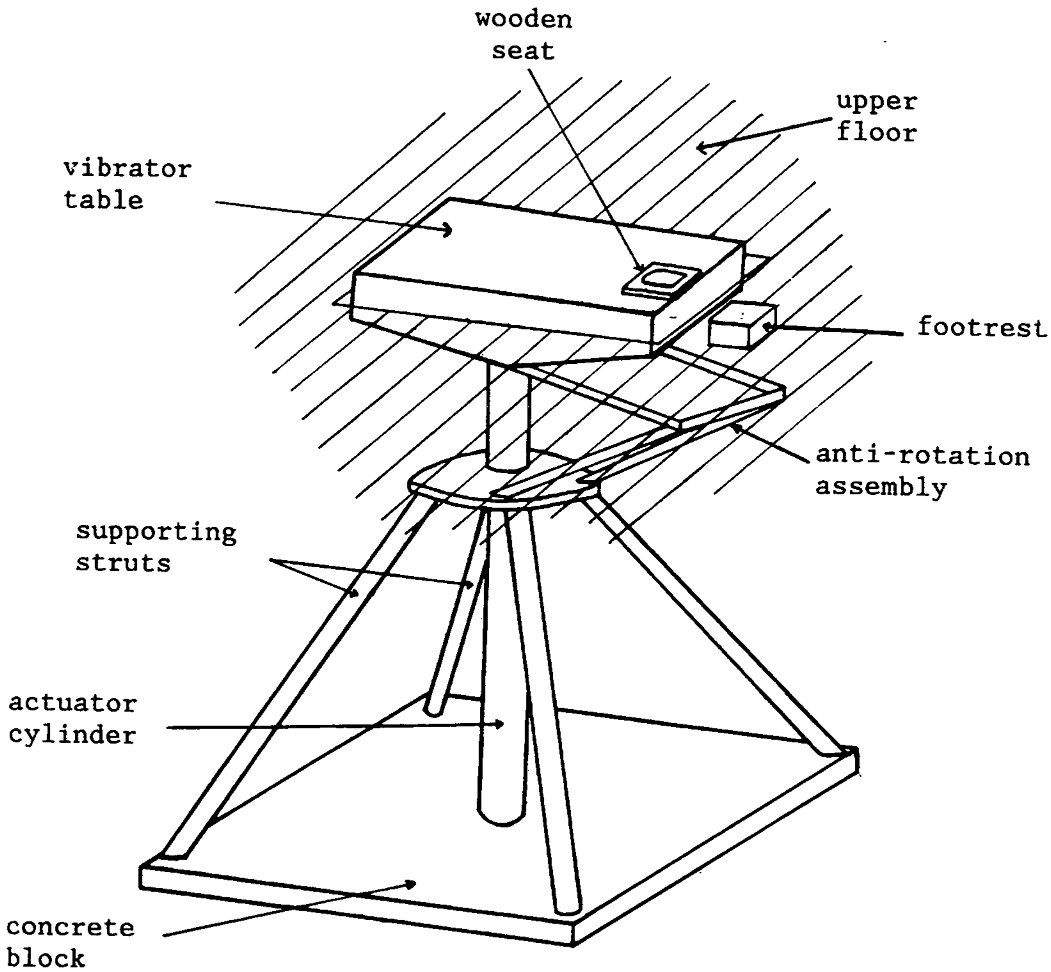

Figure 3.12 Schematic diagram of the one-metre stroke vertical hydraulic vibrator employed in Experiment 5.

3.3.1.2 Apparatus for Generation of Horizontal (y-axis) Vibration

For Experiment 5, horizontal (y-axis) whole-body vibration was produced by a one-metre stroke horizontal hydraulic vibrator. Figure 3.13 provides a schematic diagram of the vibrator system. A steel base carried two guide rails which supported a moving carriage guided by four guide bushes. Each guide bush contained three hydrostatic pads. Hydrostatic bearings enabled no direct contact between the main guides and the bushes. This facilitated very low friction movement of the carriage. A load platform was connected to the carriage. The drive system of the platform consisted of two actuator cylinders which were clamped on to the base in the same way as the main guides. Piston rods slid freely within the actuators.

The subjects sat on a contoured rigid wooden seat (Figure 3.2) secured to the longitudinal side of the platform. Their feet and thighs were positioned horizontally and the lower legs vertically by means of an adjustable, stationary footrest placed beside the platform. There was no backrest.

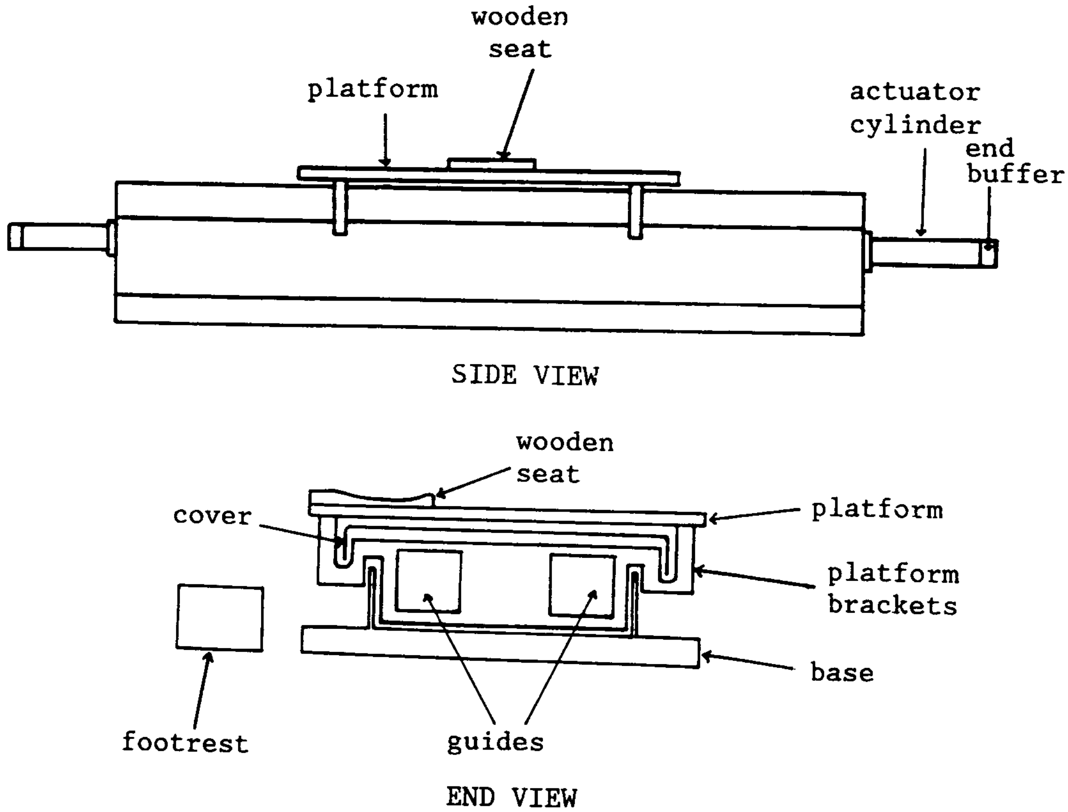

Figure 3.13 Schematic diagrams of the one-metre stroke horizontal hydraulic vibrator employed in Experiment 5.

3.3.2 Generation of Vibration Stimuli

The acceleration time histories of the vibration stimuli presented in Experiment 6 were frequency weighted to compensate for the response of the vibrator-subject combination using the method described in Section 3.2.3. Figures 3.14 and 3.15 show the frequency response functions of the one-metre stroke vertical and one-metre stroke horizontal hydraulic vibrators respectively.

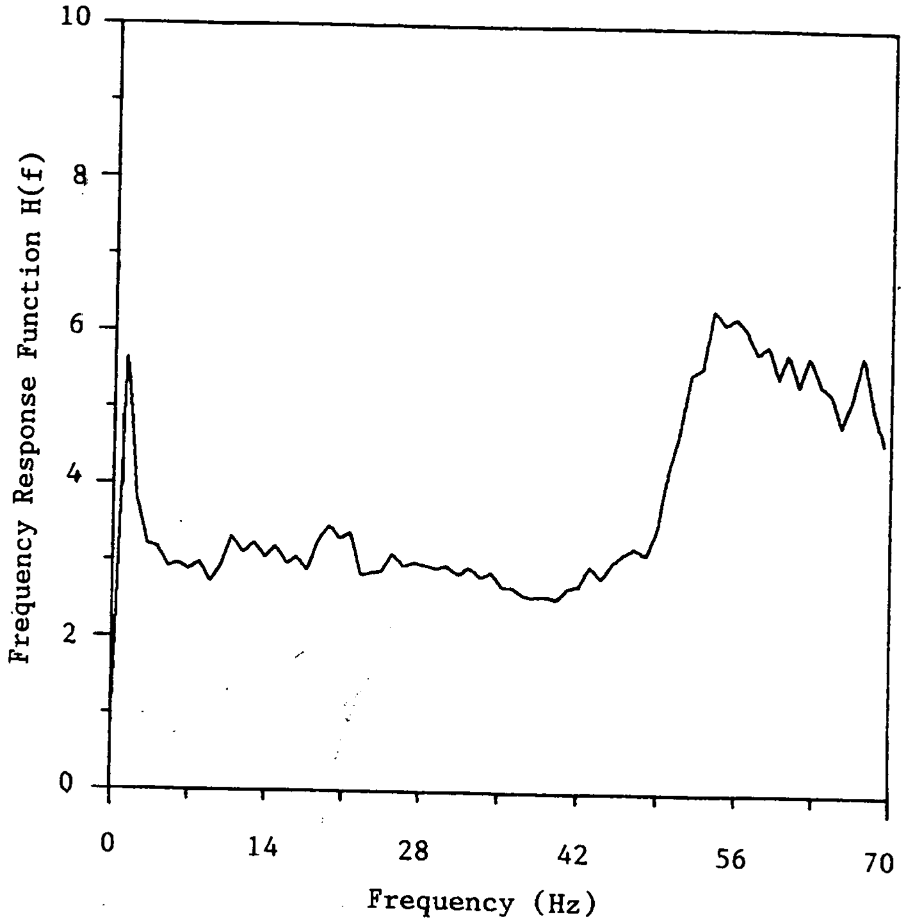

Figure 3.14 Frequency response function of one-metre stroke vertical hydraulic vibrator.

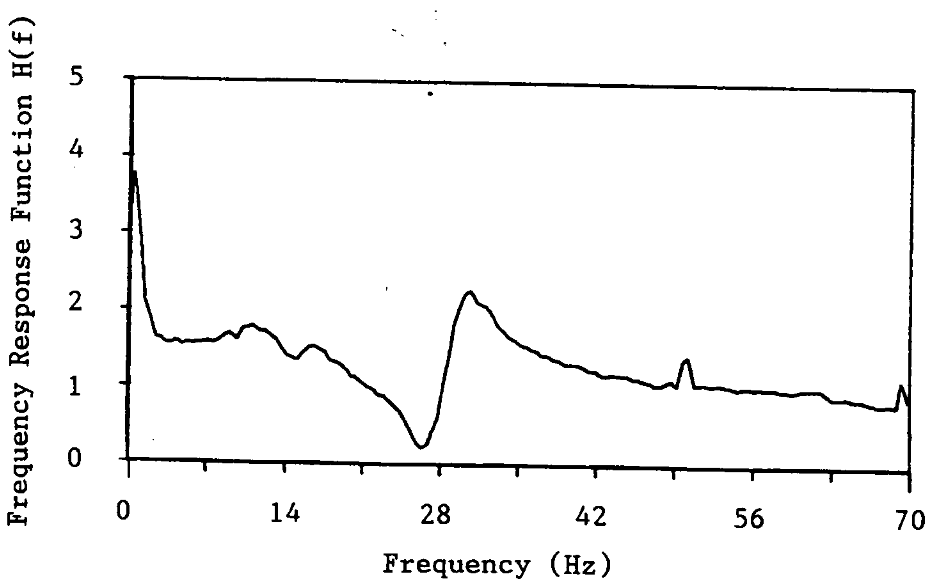

Figure 3.15 Frequency response function of one-metre stroke horizontal hydraulic vibrator.

3.3.2.1 *Intersubject Variability*

The average standard deviation of the magnitudes of each stimulus presented in Experiment 5 was 6.4% and 2.6% of the mean acceleration magnitude of each stimulus for vertical and horizontal vibration respectively.

3.3.2.2 *Cross-Axis Coupling*

Tables 3.1 and 3.2 show the cross-axis coupling for the vertical and horizontal sessions. The values are given as the motion in the two cross-axes expressed as a percentage of motion in the principal axis. For the z-axis session, y-axis motion was less than 40% and x-axis motion was less than 24% of z-axis motion. For the y-axis session, z-axis and x-axis motions were less than 28% of y-axis motion. For both sessions, motion in the two cross-axes was mostly insignificant because it occurred at 50 Hz where sensitivity to vibration is low. However, with high frequencies of vibration, cross-axis coupling occurred at the test frequency and may have influenced response to horizontal motion.

z-axis magnitude (ms^{-2} r.m.s.)		Frequency (Hz) 4	5.6	8	11.3	16	22.5	31.5	44.5	63
0.04	y-axis motion (% of z)	40	39	39	38	36	31	28	34	36
	x-axis motion (% of z)	12	11	11	14	11	9	13	20	8
0.16	y-axis motion (% of z)	10	12	11	10	10	8	15	12	25
	x-axis motion (% of z)	3	3	3	3	3	5	21	15	5
0.40	y-axis motion (% of z)	3	3	3	3	3	7	11	7	25
	x-axis motion (% of z)	1	1	1	1	2	7	24	18	5

Table 3.1 Cross-axis coupling for vertical motion.

y-axis magnitude (ms^{-2} r.m.s.)		Frequency (Hz) 4	5.6	8	11.3	16	22.5	31.5	44.5	63
0.04	z-axis motion (% of y)	21	17	14	15	15	14	17	18	24
	x-axis motion (% of y)	21	21	21	21	21	18	31	21	29
0.16	z-axis motion (% of y)	5	5	6	5	6	6	28	6	10
	x-axis motion (% of y)	6	6	6	5	6	6	28	6	10
0.40	z-axis motion (% of y)	1	1	1	1	3	2	5	5	13
	x-axis motion (% of y)	1	1	1	3	4	1	25	4	9

Table 3.2 Cross-axis coupling for horizontal motion.

3.3.2.3 Background Vibration

The mean background vibration was 0.032 ms^{-2} r.m.s. (standard deviation, σ_{n-1} = 0.005) in the z-axis and 0.027 ms^{-2} r.m.s. (standard deviation, σ_{n-1} = 0.002) in the y-axis, with most energy at 50 Hz. According to Parsons (1982, 1983) the background vibration for both sessions would not be perceptible to the average subject.

The results presented were based on the measured r.m.s. acceleration after appropriate r.m.s. subtraction of the background motion.

3.3.2.4 *Distortion*

Table 3.3 shows the distortion present at each frequency of sinusoidal motion calculated from W_b and W_d frequency-weighted time histories for the highest, lowest and middle magnitudes of motion. The distortion is given by the following expression:

$$\text{Percentage Distortion} = 100 \left[\frac{\int_{\sqrt{2}f_0}^{200} G(f)\,df}{\int_0^{\sqrt{2}f_0} G(f)\,df} \right]^{\frac{1}{2}}$$

where G(f) is the power spectrum of vibration on the vibrator seat and f_0 is the frequency of sinusoidal motion. The distortion figures are low (less than 22.1%) except for vertical motion at the lowest magnitude. These high levels of distortion were due to the background vibration which occurred at 50 Hz: though it was unlikely to have been perceptible, it resulted in large distortion figures at the lowest magnitudes.

	% DISTORTION					
Frequency (Hz)	Vertical Acceleration (ms^{-2} r.m.s.)			Horizontal Acceleration (ms^{-2} r.m.s.)		
	0.04	0.16	0.40	0.04	0.16	0.40
4.0	94.4	18.6	7.9	8.4	4.4	4.1
5.6	83.8	14.0	5.7	9.6	3.2	2.4
8.0	86.6	12.1	4.5	12.1	3.4	1.9
11.3	58.3	10.1	4.1	12.6	3.9	1.5
16.0	50.6	9.4	3.9	10.6	4.8	1.9
22.5	35.7	9.3	4.0	19.5	5.7	2.6
31.5	35.4	10.0	4.4	22.1	8.0	3.6
44.5	5.5	3.7	1.8	1.4	0.6	0.5
63.0	5.1	2.0	1.0	0.6	0.4	0.3

Table 3.3 Distortion percentages for three magnitudes of motion.

3.3.3 Apparatus for Noise Generation

For Experiment 5, a $^{1}/_{3}$-octave band noise stimulus was generated by a Bruel and Kjaer noise generator, a Bruel and Kjaer $^{1}/_{3}$-octave filter set and a Technics SU-V4X amplifier. The sound was presented to the subjects via 1.5 cm diameter KOSS KMP/2 miniature earphones fitted with removable sponge covers and positioned at the entrance to the auditory canals. The subjects also wore Bilsom Viking 2318 circumaural ear defenders over the miniature earphones to reduce extraneous noise. A Kemar artificial eardrum was employed to calibrate the noise generation system.

3.3.4 Background Noise

The ambient acoustic noise received by the subjects (when wearing ear defenders) was 31.5 dB(A) for the vertical session and 36 dB(A) for the horizontal session. The ambient noise level was determined by measuring at the position occupied by the subject's head and then applying the attenuation of the ear defenders based on the specifications provided by the manufacturer. For a few stimuli, the vibrator platform produced an acoustic noise. The noise was loudest at the highest magnitude of motion. For vertical motion at 0.40 ms^{-2} r.m.s., the sound pressure level measured at the position of the subject's head was 54 dB(A), 45 dB(A), 44 dB(A) and 41 dB(A) for 63 Hz, 44.5 Hz, 31.5 Hz and 22.5 Hz vibration respectively, applying the appropriate attenuation of the ear defenders. For vertical motion at 0.20 ms^{-2} r.m.s., the sound pressure level was 47 dB(A), 41 dB(A) and 43 dB(A) for 63 Hz, 44.5 Hz and 31.5 Hz vibration respectively. For horizontal motion, only two stimuli produced significant noise: at 0.40 ms^{-2} r.m.s. the sound pressure level was 39 dB(A) and 37 dB(A) for 63 Hz and 44.5 Hz vibration respectively. It might be expected that an increase in acoustic noise would increase the subjective response to the vibration stimuli but there was no evidence of such an effect.

CHAPTER 4

THE ANNOYANCE PRODUCED BY INTERMITTENT RAILWAY-INDUCED BUILDING VIBRATION

4.1 INTRODUCTION

The vibration produced in buildings during the passage of nearby trains consists of variable durations of intermittent events. A means of indicating the annoyance caused by railway-induced building vibration must accumulate the motion over time in a manner which allows for the time dependency of subjective reaction to whole-body vibration. Section 2.3 provides a review of experimental investigations of the effect of duration on the response to vibration and shows there is little agreement between the results of previous studies.

The International Standard ISO 2631 (1974) provides a guide to the acceptability of whole-body vibration for stimuli of durations from 1 minute to 24 hours. The allowable magnitudes proposed change very little between 1 minute and 10 minutes. Between 10 minutes and 8 hours they correspond approximately to root-mean-square averaging which is the most common method currently used to quantify average vibration magnitude (r.m.s. = $(1/T \int_0^T a^2(t)\ dt)^{\frac{1}{2}}$ where a(t) is the frequency weighted acceleration and T is the duration of exposure). Root-mean-square averaging implies a time dependency given by (acceleration magnitude)^2 x time = constant. This suggests that to maintain the same degree of discomfort with a four fold increase in vibration duration, the vibration magnitude should be decreased by a factor of two.

However, there is some evidence to suggest that a time dependency defined by an exponent of 2 relating magnitude and duration overestimates the effect of duration on subjective response to vibration. The results of a study by Miwa (1968b) indicated an exponent of 2.9 for exposure durations from 0.007 seconds to 6 seconds. The findings of Kjellberg and Wikstrom (1985b) indicated an exponent generally between 4 and 7.7 for durations up to 3 seconds. Griffin and Whitham (1980a,b) determined an exponent of between 2.2 and 4 for exposure durations up to 32 seconds. Griffin and Whitham proposed that a time dependency implied by the root-mean-quad procedure ($a^4t = k$) may be applicable to long duration exposures as well as to short duration exposures (r.m.q. = $(1/T \int_0^T a^4(t)\ dt)^{1/4}$). An exponent of 4 indicates that to maintain the same degree of discomfort with a doubling of the vibration magnitude, the exposure duration should be decreased 16 fold.

British Standard 6472 (1984), "Guide to the evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)", states that the root-mean-quad of the weighted acceleration signal may be used as an alternative method of assessing the average vibration magnitude of impulsive events. However, since long periods of vibration are more unpleasant than short periods, it is desirable for a unit of measurement to provide a measure of the total strength of a signal appropriately accumulated over time and not merely the average value. The vibration dose value was proposed by Griffin (1982, 1984) as a method of vibration evaluation and is employed in the British Standard 6841 (1987). The vibration dose value is given by:

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

where the a(t) is the acceleration time history (ms^{-2}) and t is the time (seconds); T is the total period of time during which exposure to vibration may occur (seconds). The vibration dose value is an accumulative measure of vibration. It provides a means of quantifying the severity of vibration which depends on both the magnitude of the vibration and the duration over which the vibration occurs.

Previous investigations have provided insufficient evidence of the time dependency of subjective reaction to intermittent events such as vibration from passing trains. The present study consisted of two experiments involving intermittent events. The first experiment sought to quantify how the annoyance caused by simulated railway-induced building vibration depended on how frequently the trains passed. It also investigated the manner in which annoyance depended on the magnitude of vibration. The trade-off between the number of passing trains and the magnitude of the vibration was determined from the results of the first experiment. The aim of the second experiment was to confirm that the relation between the number of passing trains and the magnitude of vibration could be used to predict conditions which would cause different degrees of annoyance.

4.2 APPARATUS

Experiments 1 and 2 took place in a room which was modified so as to provide a reasonable representation of a small comfortable sitting-room. Subjects sat on a contoured wooden seat, secured to the vibrator table which was constrained to move in the vertical (z-axis) direction only. The seat was driven by a Derritron VP30 electromagnetic vibrator, powered by a 300 watt amplifier. A footrest and a wooden backrest, which was slightly contoured for comfort, did not vibrate.

The acceleration time history of the vibration stimulus presented in the two experiments was frequency weighted to compensate for the frequency response of the vibrator-subject combination (see Section 3.2.3). An accelerometer positioned under the centre of the seat measured the acceleration received by the subjects. Computer-generated vibration stimuli were used as the input to the vibrator amplifier via a 10 bit digital-to-analogue converter and an eight pole Butterworth low-pass filter at 100 Hz (48 dB per octave roll-off). The digital-to-analogue and analogue-to-digital sampling rate was 256 samples per second.

Section 3.2 provides full details of the apparatus, generation of the vibration stimuli and performance of the vibrator.

4.3 SUBJECTIVE METHOD OF ASSESSMENT

Experiments 1 and 2 employed a simple seven-point scale for assessment of the stimuli by a rating method. The subjects were shown a scale marked from zero to six, where zero was indicated to correspond to "not annoyed" and six was indicated to correspond to "extremely annoyed" (Appendices 4.1 and 4.2).

Magnitude estimation and magnitude production techniques have been used by previous experimenters to investigate subjective reaction to vibration (e.g. Hiramatsu and Griffin (1984), Kjellberg and Wikstrom (1985b)). However, these methods were not suitable for Experiments 1 and 2 since they require comparison of the test stimuli with a reference stimulus. The rating method enabled the subjects to provide an indication of the annoyance produced by intermittent vibration without comparison of the motion with a reference stimulus. The semantic scaling method is often used to determine the subjective reaction to vibration stimuli (e.g. Clarke and Oborne, 1975b). However, the rating method has several advantages over semantic scaling. The latter involves providing the subject with a choice of adjectives which may be used to describe, for example, the degree of annoyance produced by the stimuli. The method of semantic scaling may appear useful but its use is limited because the scale is only ordinal so that the relationship between labels on the same scale cannot be quantified. The rating method allows the assignment of numbers to stimuli. The ratio scale which results is far more useful than the ordinal scale resulting from semantic scaling, since the quantitative relationship between responses can be determined.

4.4 EXPERIMENT ONE: EFFECT ON ANNOYANCE OF NUMBER OF TRAINS AND MAGNITUDE OF VIBRATION

4.4.1 Introduction

The experiment was divided into two parts, conducted in a single session. Part 1 investigated whether the annoyance caused by simulated railway-induced building vibration depended on how frequently the trains pass. Forty-eight subjects employed a seven-point scale to assess the annoyance caused by a one-hour session during which they were exposed to between four and 32 simulations of vibration from a passing train. Part 2 investigated how the magnitude of the vibration affected annoyance. The seven-point scale was employed to indicate annoyance from vibration stimuli presented at six magnitudes.

4.4.2 Experimental Method

4.4.2.1 Subjects

The selection of subjects was made such that a typical sample of the community was represented. On this basis, 50 percent of the subjects were male, 50 percent were female. Fifty percent of the subjects were under 35 years of age and 50 percent were over 35 years.

Twenty-four men and twenty-four women acted as paid subjects in the experiment. Of the 48 subjects, 12 men and 12 women were aged between 18 and 34 years and 12 men and 12 women were between 35 and 60 years. All subjects were shown a list of medical conditions which might have rendered them unfit for participation in the experiment (BSI, 1973).

4.4.2.2 *Part 1: Effect of Number of Trains*

Procedure

The first part of the experiment was conducted to investigate the effect of the number of passing trains and involved four conditions. The differences between conditions were the number of simulations of railway-induced building vibration. These were 4, 8, 16 and 32 repetitions of the same train in one hour at equal intervals. The numbers of trains were selected so as to provide a large range of realistic conditions. Each of the 48 subjects experienced only one of the conditions. For this purpose they were divided into four groups of 12, with equal numbers in each group of men and women and of over 35 years and under 35 years of age.

The subjects were instructed to sit in a comfortable upright posture on a wooden seat attached to the vibrator table. The feet and upper legs of each subject were positioned horizontally and the lower legs vertically by means of an adjustable stationary footrest.

Before the start of the experiment the subjects were given the instructions shown in Appendix 4.1, which described the use of a seven-point scale to assess the one hour session as a whole. During the session, the subjects were encouraged to read material of their choice. After one hour they were asked to respond in the manner indicated in the instructions.

Stimuli

A single vibration stimulus was repeated during the hour. It consisted of a simulation of the z-axis vibration recorded in a house during the passage of a nearby diesel multiple unit. The duration of the stimulus was 12.5 seconds with a root-mean-square acceleration of 0.059 ms^{-2} averaging over the exposure duration. The magnitude of the original recording was 0.037 ms^{-2} r.m.s. The frequency range of the stimulus was 2 Hz to 50 Hz which is typical of vibration in buildings. Most of the energy occurred at 13 Hz. Figures 4.1 and 4.2 show the acceleration time history and the power spectrum of the stimulus.

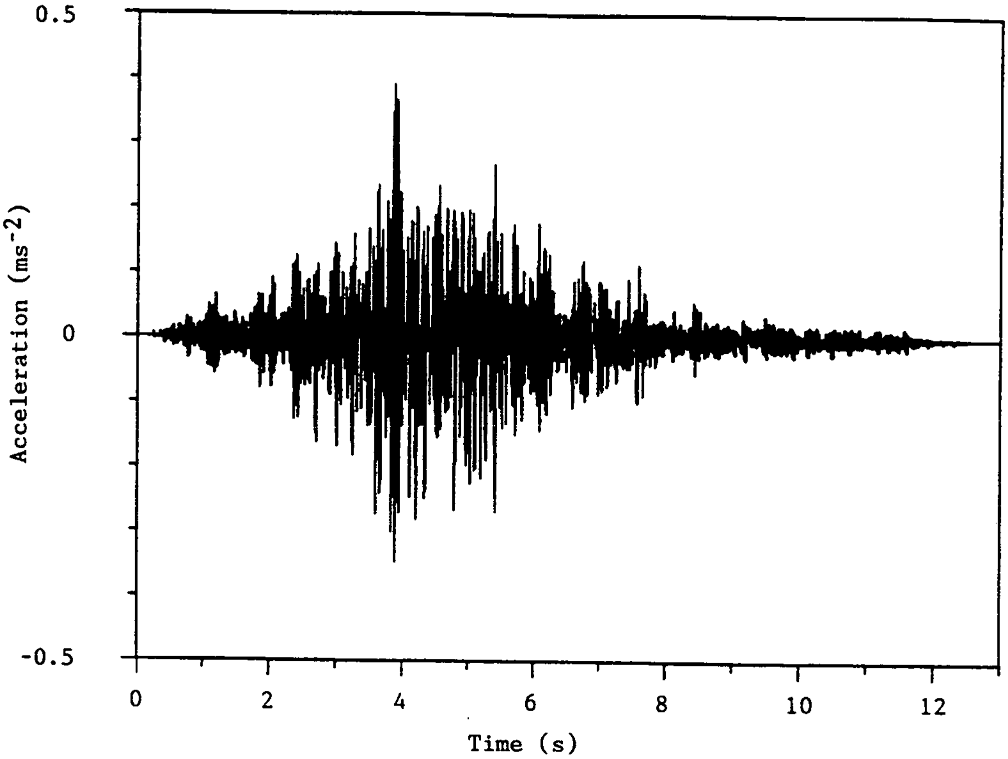

Figure 4.1 Acceleration time history of the stimulus.

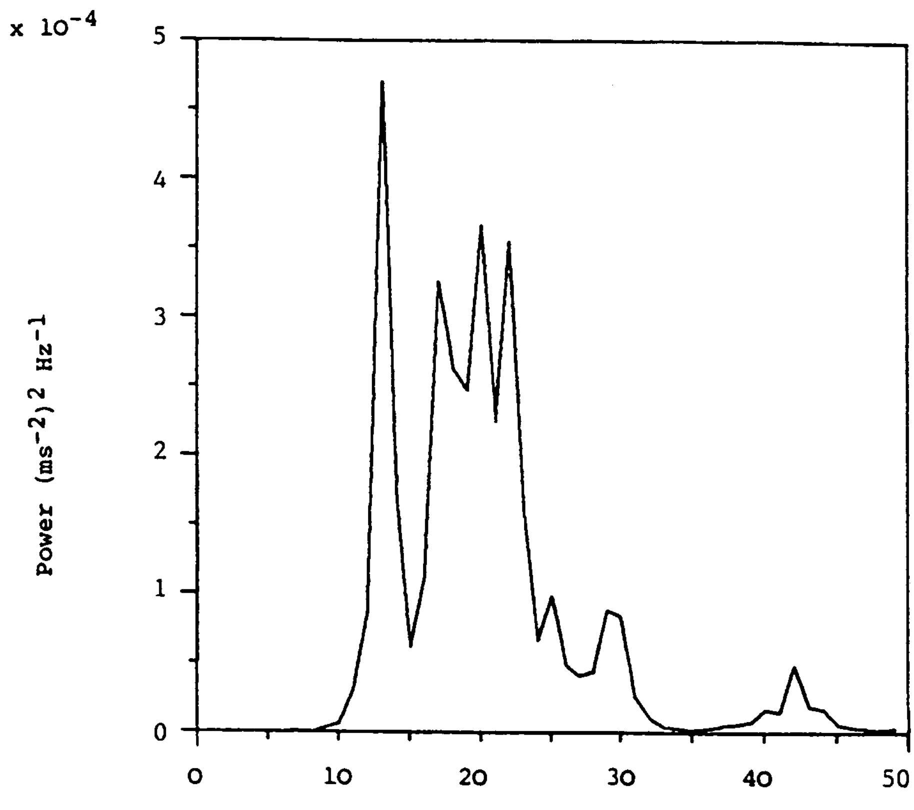

Figure 4.2 Acceleration power spectral density of the stimulus. Resolution 1 Hz, degrees of freedom = 48.

4.4.2.3 *Part 2: Effect of Magnitude of Vibration*

Procedure

Part 2, which was 10 minutes in duration, followed immediately after Part 1 and involved the exposure of each subject to six stimuli presented twice in a random order. After each stimulus, the subjects were requested to respond using the same scale employed in Part 1. The instructions for Part 2 are shown in Appendix 4.2.

Stimuli

The 12 vibration stimuli presented in Part 2 were the same as the stimulus presented in Part 1 but multiplied by six different factors: 0.63, 0.80, 1.00, 1.25, 1.60 and 2.00, to give overall r.m.s. acceleration magnitudes of 0.037, 0.047, 0.059, 0.074, 0.094 and 0.118 ms^{-2}. The six magnitudes of the stimuli were presented twice to each subject in an order determined from a six by six latin square.

4.4.3 Results

4.4.3.1 *Part 1: Effect of Number of Trains*

Figure 4.3 shows the mean annoyance rating for each number of passing trains. Linear regression analysis by the least squares fit applied to the individual results gave the relation between the number of trains, N, and the annoyance rating, R, as:

$$R = 0.055\ N + 1.26$$

The correlation coefficient ($r = 0.45$) was highly significant ($p < 0.005$).

The Mann–Whitney U test (see Siegel, 1956) was applied to the annoyance ratings to determine whether there was a significant difference between the annoyance ratings obtained for each of the four conditions (number of trains). Table 4.1 gives the significance of differences determined from the application of the Mann–Whitney U test between all possible paired combinations of the four conditions. There was a large spread of ratings at each condition. Only when conditions were paired with the condition consisting of 32 trains per hour were the differences significant ($p < 0.05$). This result is illustrated in Figure 4.3.

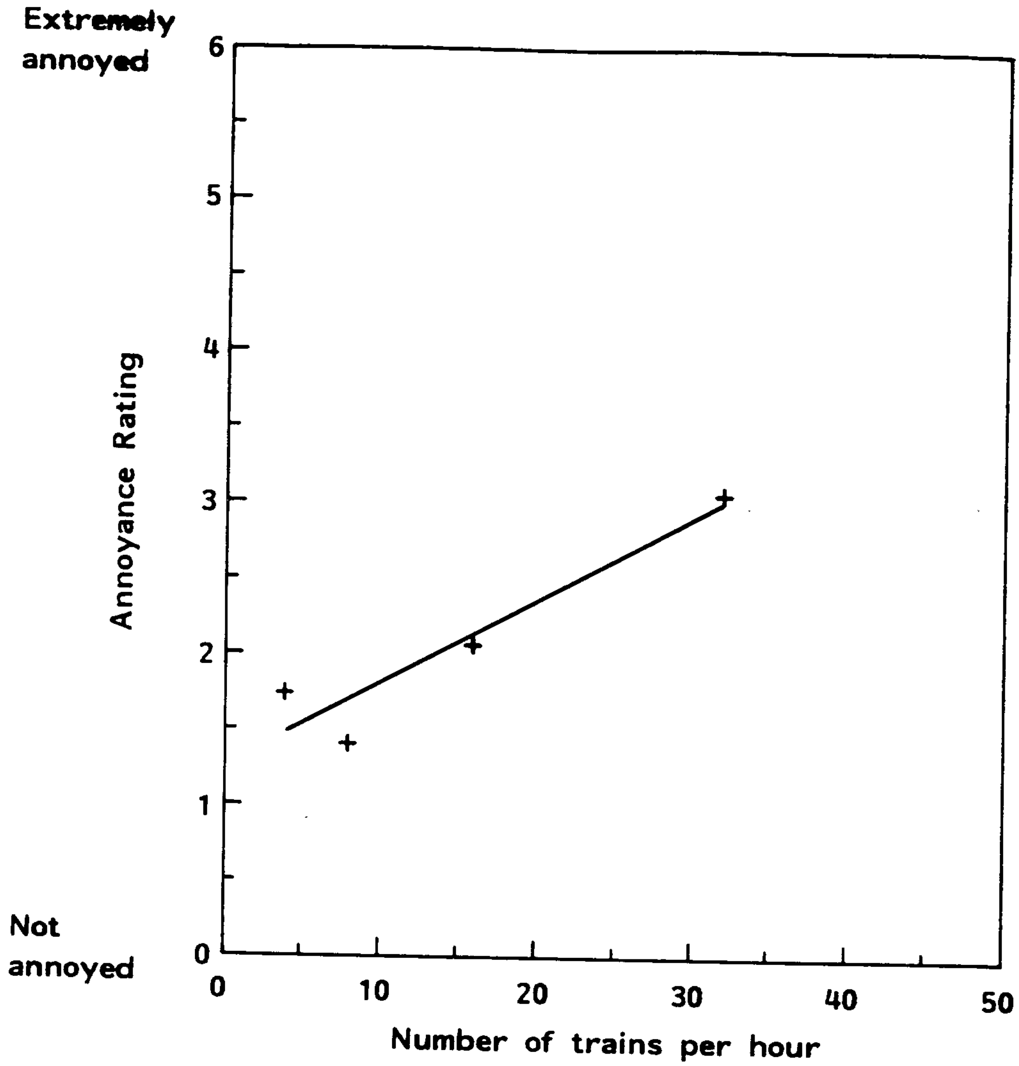

Figure 4.3 Relation between annoyance and number of trains.

Number of trains per hour		4	8	16	32
Number of trains per hour	4		-	-	**
	8			-	**
	16				*
	32				

- not significant
* $p < 0.05$
** $p < 0.01$

Table 4.1 Significance of differences between annoyance ratings for the four conditions (Mann-Whitney U).

4.4.3.2 Part 2: Effect of Magnitude of Vibration

Difference between First and Second Presentations

For Part 2 of the experiment, the random order of six magnitudes of the train was presented twice. The Wilcoxon matched–pairs sign rank test (see Siegel, 1956) was applied to determine whether there was a significant difference between the annoyance caused by the first and second presentations at each magnitude. The results of the test showed that there was no significant difference between the annoyance caused by the first presentation and the second presentation at any of the six magnitudes. Therefore, it can be concluded that the annoyance of the subject was not affected by the presentation of previous stimuli and further analysis was conducted by combining the results for the first and second presentations.

Effect of Order

For Part 2 of the experiment, a latin square design was employed to provide six different random orders of the six magnitudes. It was necessary to determine whether there was a bias introduced in the results by the order in which the stimuli were presented. The effect of order was examined by looking at the effect of when a particular magnitude of stimulus was presented, e.g. first, second .... last.

Kruskal–Wallis one–way analysis of variance (see Siegel, 1956) was applied to the ratings of the lowest magnitude stimulus and then to the highest magnitude. The results showed that there was no significant difference between the results of each position for the lowest magnitude and for the highest magnitude. It was assumed that there was no effect of position at any magnitude and hence it was not necessary to compensate for any bias introduced in the results by the order of presentation of the stimuli.

4.4.3.3 Relation between Number of Trains, Magnitude and Annoyance

A relation between the magnitude of the vibration and the annoyance was determined for each subject by linear least squares regression applied to the results of Part 2. The annoyance rating from Part 1 for each subject was replaced by an equivalent magnitude of vibration according to the individual fitted line from Part 2. Figure 4.4 illustrates a typical result. This subject indicated an annoyance rating of 2 for Part 1, in which eight trains were presented in one hour. The annoyance rating from Part 1 was replaced by an equivalent magnitude of 0.051

ms^{-2} r.m.s.

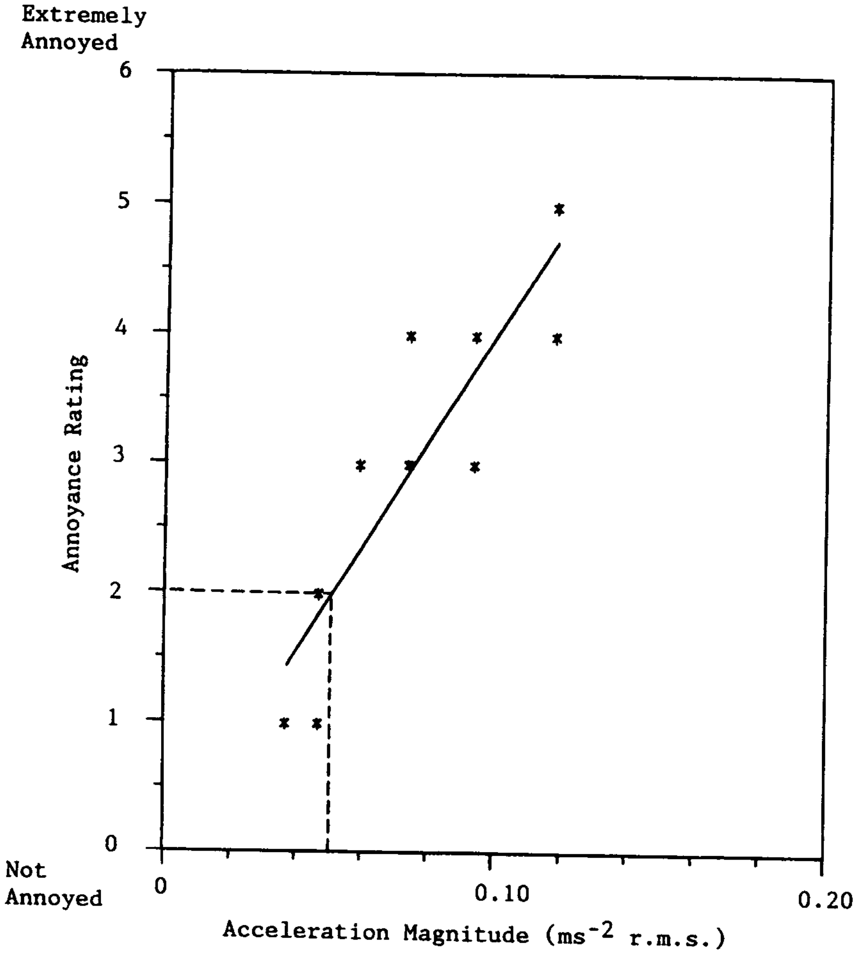

Figure 4.4 A typical result for Part 2. Relation between annoyance and magnitude.

A relationship was then determined between the equivalent magnitude and the number of trains using the annoyance ratings from all subjects. Appendix 4.3 provides the intercept and gradient of the individual regression equations from Part 2 relating annoyance rating and magnitude. The appendix also shows the annoyance ratings from Part 1 and the corresponding equivalent magnitudes.

Determination of equivalent magnitude yielded a negative value for four of the 48 subjects. This situation arose when a subject's assessment of the annoyance produced by periodic presentation of trains over an hour in Part 1 was less than the annoyance produced by any single train presented in Part 2 and also the gradient of the regression line was small. Negative equivalent magnitudes cannot be true values and the results from these subjects were not included in the analysis.

The Mann–Whitney U test (Seigel, 1956) was applied to the remaining 44 equivalent magnitudes to determine whether there existed a significant difference between the equivalent magnitudes of each of the four conditions. Table 4.2 gives the significance of the differences, determined from the application of the Mann–Whitney U test, between all combinations of pairs of the four conditions. There was a large spread of values at each condition as shown in Figure 4.5. Again, the differences between the ratings of the four conditions were significant ($p < 0.05$) only when paired with the condition consisting of 32 trains per hour. The correlation coefficient ($r = 0.40$) for equivalent magnitude as a function of number of trains was highly significant ($p < 0.005$).

Number of trains per hour	4	8	16	32
4		-	-	**
8			-	**
16				*
32				

- not significant
* $p < 0.025$
** $p < 0.01$

Table 4.2 Significance of differences between equivalent magnitudes of the four conditions (Mann–Whitney U).

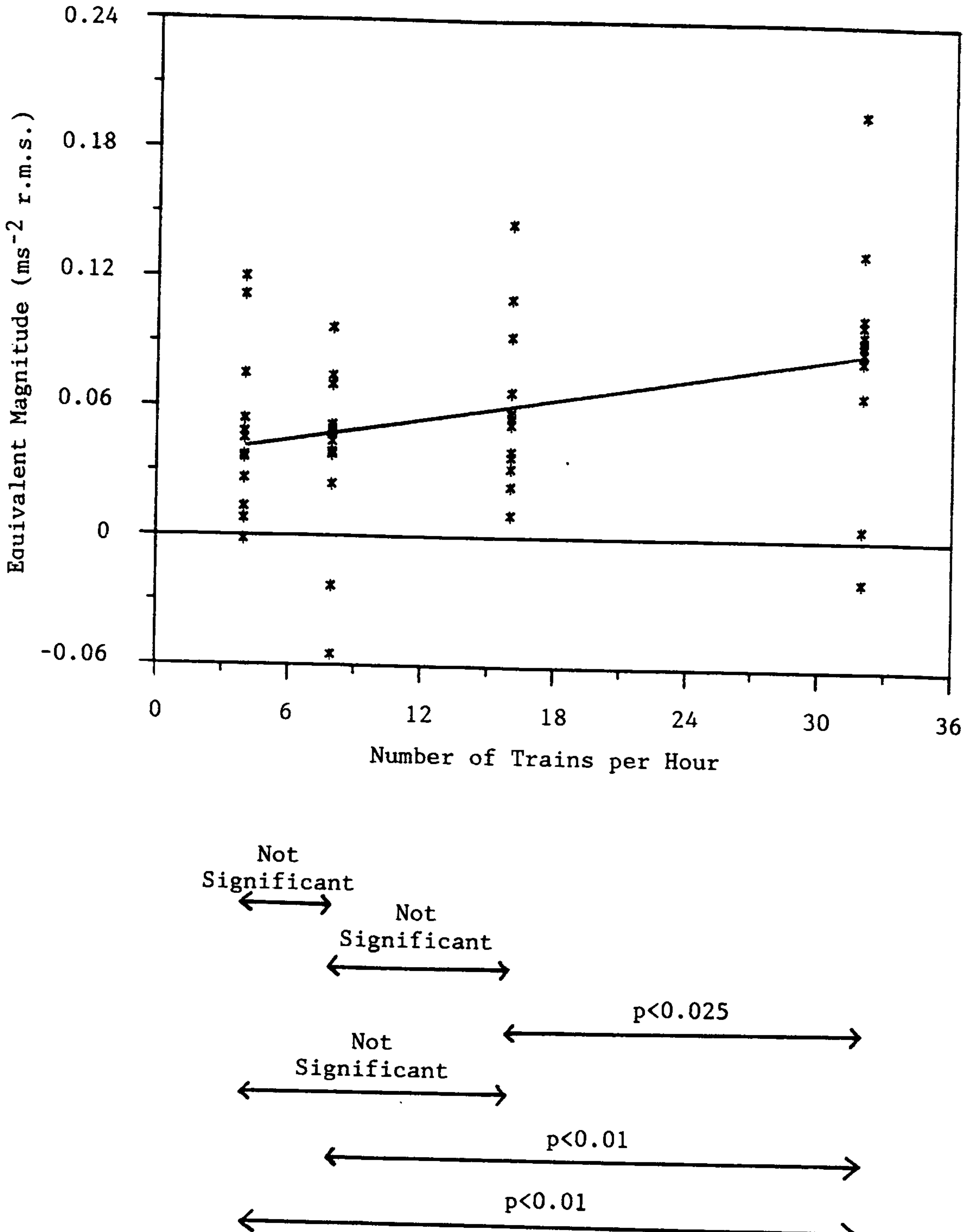

Figure 4.5 Relation between equivalent magnitude of vibration and number of trains with significance of difference between conditions.

Effect of Age and Sex

The Mann-Whitney U test was applied to the equivalent magnitudes of vibration of all subjects to determine whether there was a significant difference between the results of men and women or between the results of subjects over and under 35 years of age. Table 4.3 shows the results of the test which indicate that there was no significant effect of age or sex on the results. (The equivalent magnitudes from female subjects were almost significantly larger than from male subjects.)

Test for effect of age or sex	Significance of differences (p)
Men and women	$p = 0.058$ not significant
Over and under 35	$p = 0.151$ not significant

Table 4.3 Effect of age and sex (Mann-Whitney U).

4.4.3.4 Determination of an Accumulative Measure of Exposure

An accumulative measure of exposure relating the magnitude of induced vibration, V, with the number of trains, N, was determined by fitting a straight line by the method of least squares to the logarithm of the equivalent magnitude of vibration as a function of the logarithm of the number of trains. A relationship was determined in the form:

$$\log V = m \log N + \log k$$

where m is the gradient of the line and k is a constant. This relationship may be written in the psychophysical power law form:

$$V = kN^{m}$$

Figure 4.6 shows the logarithm of the equivalent magnitude as a function of the number of trains. The equation of the line is given by:

$$\log_{10} V = 0.27 \log_{10} N + \log_{10} k_1$$

which can be written as:

$$V = k_1 N^{0.27}$$

from which:

$$V^{3.7} = k_2 N$$

where k_1 and k_2 are constants. The correlation coefficient ($r = 0.29$) was significant ($p < 0.025$). This result suggests that a doubling of the vibration magnitude produces approximately the same increase in annoyance as a 16 fold increase in the number of trains (i.e. $N \alpha V^4$). A trade-off between vibration magnitude and number of trains is obtained from the relation for constant annoyance which is given by:

$$N \alpha V^{-3.7}$$

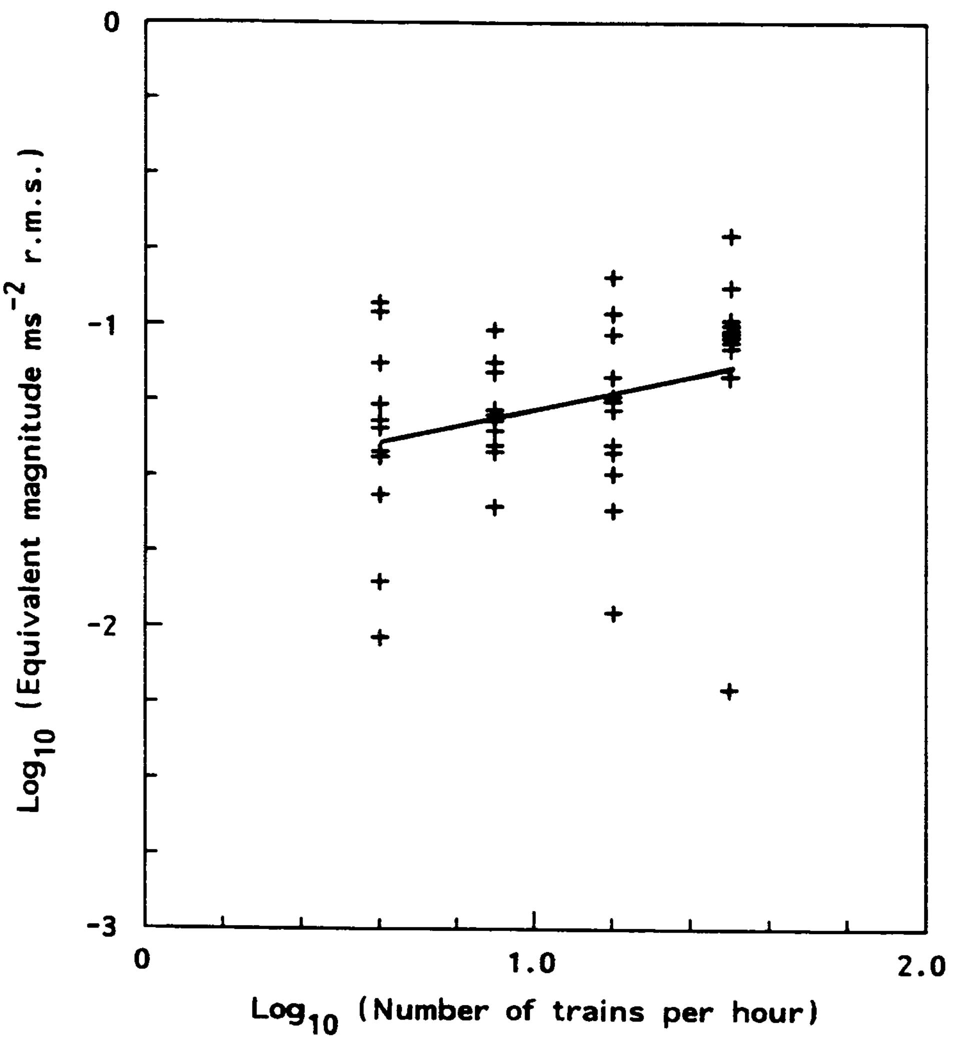

Figure 4.6 Relation between logarithm of number of trains and logarithm of equivalent magnitude.

An alternative method of determining a measure for accumulative exposure may be defined by the use of a regression between mean values obtained in Parts 1 and 2. The mean annoyance of the four groups of 12 subjects at each condition in Part 1 is then replaced by an equivalent magnitude determined using the appropriate relationship for the same 12 subjects found in Part 2. An advantage of this method is that the mean values produced no negative equivalent magnitudes so that the results from all subjects could be employed in the analysis. The relationship for equal annoyance obtained by this method was very similar to the relationship obtained by the method which used the individual results and is given by:

$$N \alpha V^{-3.5}$$

4.4.4 Discussion and Conclusions

The annoyance caused by simulated railway-induced building vibration has been shown to depend on both how frequently trains pass and on the magnitude of the vibration produced by the passing train. There was a large spread of annoyance ratings and of the corresponding equivalent magnitudes for each number of trains per hour. Statistical analysis showed that there was no significant difference between the results of conditions with smaller numbers of trains. However, the differences were significant between conditions paired with the condition consisting of 32 trains per hour. The correlation coefficients for annoyance rating and equivalent magnitude as a function of the number of trains on linear coordinates were both highly significant ($p < 0.005$).

A relation between the number of passing trains, N, and the magnitude of vibration, V, has been determined for constant annoyance to be approximately $N \alpha V^{-4}$. An alternative method of determining such a relation from the mean data yielded very similar results. The first method described is the most precise, but had the disadvantage of yielding four negative values of equivalent magnitude which must be discarded from the analysis. The alternative method avoided negative equivalent magnitudes but, since mean values were used, the method takes less account of individual variation in sensitivity and may be considered to be less exact.

The relation, $N \alpha V^{-4}$, provides a trade-off between vibration magnitude and number of trains and suggests that to maintain the same degree of annoyance with a doubling of the vibration magnitude, the number of trains should be decreased 16 fold.

4.5 EXPERIMENT TWO: ASSESSMENT OF THE RELATION BETWEEN NUMBER OF TRAINS AND MAGNITUDE OF VIBRATION

4.5.1 Introduction

The first experiment determined a relation between the number of passing trains per hour, N, and the magnitude of vibration, V, for constant annoyance to be approximately:

$$N \alpha V^{-4}$$

The second experiment employed the findings of the first experiment and sought to confirm the degree to which the vibration magnitude must be reduced for any increased annoyance with more trains to be counteracted.

Two relations between the number of trains and the magnitude of vibration were employed: $N \alpha V^{-4}$, which was the relation determined in the first experiment, and also $N \alpha V^{-2}$. The latter was used since a common measure of the strength of a signal is its root-mean-square value which is given by:

$$\text{root-mean-square acceleration} = \left(\frac{1}{T} \int_0^T a^2(t)\, dt\right)^{\frac{1}{2}}$$

where a(t) is the frequency weighted acceleration time history and T is the duration of exposure. Root-mean-square averaging implies a time dependency given by (acceleration magnitude)^2 x time = constant and implies that to maintain the same degree of annoyance with a doubling of the vibration magnitude, the number of trains should be decreased four fold.

Three conditions were investigated: four and 32 trains per hour with two different vibration magnitudes at the lower rate. Thirty-six subjects used the same seven-point scale employed in Experiment 1 to indicate the annoyance from either four or 32 vibration stimuli presented during a one-hour period. The two vibration magnitudes at four trains per hour were selected so that the two rates would have similar effects if constant annoyance is given by either:

$$V^2N = k$$

or

$$V^4N = k$$

where k is a constant.

4.5.2 Experimental Method

4.5.2.1 Subjects

Eighteen men and eighteen women acted as paid subjects in the second experiment. In order to avoid any bias in the annoyance ratings as a result of previous experience, the selected subjects had not participated in the first experiment. Of the 36 subjects, nine men and nine women were aged between 20 and 34 years; nine men and nine women were aged between 35 and 63 years. All subjects were shown a list of medical conditions which would have rendered them unfit for participation in the experiment (BSI, 1973).

4.5.2.2 Procedure

The experiment involved a one-hour exposure to either four or 32 repetitions at equal intervals of simulated building vibration recorded during the passage of a train. If the relation $V^2N = k$ is assumed, then for the vibration magnitudes of four and 32 trains per hour to give similar annoyance:

$$32\ V_{32}^2 = 4\ V_4^2$$

so:

$$V_4 = 2.83\ V_{32}$$

where V_{32} is the magnitude of the vibration stimulus repeated at a rate of 32 per hour and V_4 is the magnitude of the vibration repeated at a rate of four per hour. For the relation $V^4N = k$, the condition for similar annoyance is:

$$V_4 = 1.68\ V_{32}$$

The subjects were divided into three groups of 12, one group receiving 32 trains per hour and the other two groups both receiving four trains per hour. The subjects sat on a wooden seat attached to the vibrator table in a comfortable upright posture. The feet and upper legs of each subject were positioned horizontally and the lower legs vertically by means of a stationary footrest. The same scale employed in Experiment 1 was used in this experiment to indicate the annoyance which would have been produced by the stimuli if felt at home. Before the start of the experiment the subjects were given instructions (Appendix 4.1) which described the use of a seven-point scale to assess the one hour session as a whole. During the session, the subjects were encouraged to read material of their choice. After one hour they were asked to respond in the manner indicated in the instructions.

4.5.2.3 Stimuli

The stimulus repeated during the hour was the same recording of railway-induced building vibration simulated in Experiment 1. The stimulus was repeated at a magnitude of 0.059 ms^{-2} r.m.s. for the group receiving 32 trains (i.e. at the magnitude presented in Experiment 1). For one of the two groups receiving four train simulations, the stimulus was repeated at a magnitude of 0.167 ms^{-2} r.m.s. (i.e. 0.059 x $(32/4)^{\frac{1}{2}}$). For the other group receiving four trains, the stimulus was repeated at a magnitude of 0.099 ms^{-2} r.m.s. (i.e. 0.059 x $(32/4)^{\frac{1}{4}}$).

4.5.3 Results

The mean annoyance ratings of the three groups of subjects are provided in Table 4.4 which shows that when the values for $(V^4N)^{\frac{1}{4}}$ are equal, the mean annoyance ratings are almost equal.

Number of trains per hour N	Magnitude of stimuli V (ms^{-2} r.m.s.)	$(V^2N)^{\frac{1}{2}}$ ($ms^{-1.5}$)	$(V^4N)^{\frac{1}{4}}$ ($ms^{-1.75}$)	Mean annoyance rating
32	0.059	0.334	0.140	2.42
4	0.099	0.198	0.140	2.17
4	0.167	0.334	0.236	3.83

Table 4.4 Mean annoyance ratings of the three conditions.

Table 4.5 shows the significance of the differences between the annoyance ratings of the three groups (Mann-Whitney U). The difference between the ratings at the two rates was not significant when the magnitudes of the stimuli were adjusted to cause similar annoyance using the relation $V^4N = k$.

Test applied between two conditions (trains per h at ms^{-2} r.m.s.)	Significance of differences (p)
32 at 0.059 and 4 at 0.099	not significant
32 at 0.059 and 4 at 0.167	< 0.025
4 at 0.099 and 4 at 0.167	< 0.01

Table 4.5 Significance of differences between annoyance ratings of the three conditions (Mann-Whitney U).

Effects of Age and Sex

Application of the Mann-Whitney U test indicated that there were no significant differences between the ratings of those over and under 35 years of age or between the ratings of men and women.

Comparison with Experiment 1

Experiments 1 and 2 both involved the presentation of 32 trains per hour at the same magnitude of 0.059 ms^{-2} r.m.s. to one group of subjects. Hence, there should be no significant difference between the results. Application of the Mann-Whitney U test indicated that the difference between the results of the two experiments for the same condition was not significant.

4.5.4 Discussion and Conclusions

The degrees of annoyance caused by the two rates of passing trains were equal when the magnitude of the vibration was adjusted using $V^4N = k$. This is consistent with the results of the first experiment and with the use of the vibration dose value for vibration assessment. When the magnitude of the vibration was adjusted using the relation $V^2N = k$, the degrees of annoyance caused by the two rates of passing trains were significantly different. This method is that implied by the use of the root-mean-square or "energy" methods. It can be concluded that the vibration dose value may be used to relate the number of passing trains to the magnitude of the induced building vibration, with respect to the annoyance produced.

Further verification of the application of the relation $V^4N = k$ was obtained by using it to predict any two of the results of this experiment from the third result. From the relation obtained, the annoyance produced by two combinations of number of trains and magnitude of vibration can be related by:

$$\left[\frac{V_1^4\ N_1}{V_2^4\ N_2}\right]^{\frac{1}{4}} = \frac{R_1}{R_2}$$

where R_1 and R_2 are the annoyance ratings.

When N_1 and N_2 were both 4, and V_1 and V_2 were 0.099 and 0.167 ms^{-2} r.m.s. respectively then:

$$\left[\frac{V_1^4\ N_1}{V_2^4\ N_2}\right]^{\frac{1}{4}} = 0.59$$

which is approximately equal to the ratio of the annoyance ratings:

$$\frac{R_1}{R_2} = 0.57$$

Similarly, when the number of trains were 4 and 32 the above relationship was in close agreement with the data: when N_1 and N_2 were 4 and 32 respectively and V_1 and V_2 were 0.059 and 0.099 ms^{-2} r.m.s. respectively then:

$$\left[\frac{V_1^4\ N_1}{V_2^4\ N_2}\right]^{\frac{1}{4}} = 0.99$$

and $$\frac{R_1}{R_2} = 0.90$$

Further, when N_1 and N_2 were 4 and 32 respectively and V_1 and V_2 were 0.059 and 0.167 ms^{-2} r.m.s. respectively then:

$$\left[\frac{V_1^4\ N_1}{V_2^4\ N_2}\right]^{\frac{1}{4}} = 1.69$$

and $$\frac{R_1}{R_2} = 1.58$$

4.6 GENERAL DISCUSSION

Exposure of subjects to vertical seat vibration while the footrest and backrest remain stationary may appear an unrealistic situation when considering human exposure to vibration in buildings. However, previous investigations have shown that footrest and backrest vibration are far less important than seat vibration. Suggs et al (1976) investigated the discomfort produced by vertical seat vibration combined with a stationary footrest and compared the results with the discomfort produced by identical seat and footrest vibration. They found that, for the frequency range 1.5 Hz to 32 Hz, discomfort was not reduced by isolation of the footrest from vibration. Griffin et al (1982) produced separate frequency weightings for translational and rotational motion of the seat and for translational motion of the backrest and footrest. The results showed that, for vertical vibration in the frequency range 1 Hz to 100 Hz, subjects were about 3.5 times more sensitive to seat vibration than footrest vibration. The results indicated greater sensitivity to vertical seat vibration than vertical backrest vibration for the frequency range 2.5 Hz to 63 Hz. The use of a stationary footrest and backrest in the present studies greatly simplified simulation of the vibration stimuli and allowed investigation of seat vibration which is far more important than backrest or footrest vibration.

Experiments 1 and 2 show that annoyance caused by railway-induced building vibration increased with an increase in the number of trains passing per hour. There was a linear relationship between annoyance and the magnitude of vibration. These findings were combined to indicate that the relation between the magnitude of vibration, V, and the number of passing trains, N, was approximately $N \alpha V^{-4}$ for equal annoyance. This relation can be related to the results of the investigation by Griffin and Whitham (1980a,b) which proposed that motions containing high peak values should be evaluated using the relation root-mean-quad ($(1/T \int_0^T a^4(t)\, dt)^{\frac{1}{4}}$ where a(t) is the acceleration and T is the averaging period).

The relation $N \alpha V^{-4}$ for equal annoyance is consistent with the use of the vibration dose value for vibration assessment which was proposed by Griffin (1982, 1984) and is employed in a method of vibration evaluation proposed by the British Standard 6841 (1987). The vibration dose value is given by $(\int_0^T a^4(t)\, dt)^{\frac{1}{4}}$ and is an accumulative measure of vibration which depends on the time over which the vibration occurs.

4.7 CONCLUSIONS

The results of Experiments 1 and 2 indicate that the root-mean-square magnitude, which is commonly used to assess the strength of vibration, is not an appropriate means of relating the magnitude of railway-induced building vibration and the number of passing trains to the annoyance produced. The relation $N \alpha V^{-4}$ provides a useful estimate of the degree to which the magnitude of the vibration induced in buildings during the passage of trains must be reduced so as to counteract any increased annoyance associated with more frequent trains.

CHAPTER 5

THE ANNOYANCE PRODUCED BY SIMULTANEOUS NOISE AND VIBRATION FROM RAILWAYS

5.1 INTRODUCTION

Most of the investigations of human response to noise and vibration have considered the reaction to the two stimuli separately. However, since railway noise and railway-induced building vibration usually occur at the same time, it is necessary to determine whether the findings of studies of the reaction to a single stimulus, i.e. noise alone or vibration alone, are applicable to a multi-stimuli environment involving both noise and vibration.

One of the first considerations regarding adverse reaction of residents to noise and vibration from a nearby railway may be to determine which of the two stimuli, noise or vibration, is causing more annoyance and hence whether a reduction in noise level or a reduction in vibration magnitude is more likely to reduce the annoyance. It follows, therefore, that determination of the relative importance of noise and vibration would be of value.

Residents in close proximity to railway lines may complain about vibration occurring during the passage of trains. However, it may be that their reaction is being influenced by the presence of simultaneous railway noise. The annoyance caused by the vibration may be reduced or increased by a reduction in the noise level. Similarly, annoyance produced by railway noise may be reduced or increased by a reduction in simultaneous railway vibration. Thus, it is important to consider the interaction of the effects of the two stimuli.

This study consisted of two experiments (Experiments 3 and 4) involving simultaneous exposure to noise and whole-body vibration. Subjects were presented with reproductions of the noise and vibration recorded in a house during the passage of a train. The experiments were conducted to investigate three aspects of subjective reaction to combined noise and vibration. Experiment 3 was conducted to determine the subjective equivalence of noise and vibration and hence the relative importance of the two stimuli. Experiment 4 sought to investigate the influence of one stimulus on the assessment of the other stimulus. It also provided information on the combined effects of railway noise and vibration. The findings were employed to determine a means of combining the effects of the individual stimuli to provide a measure of the annoyance which may be caused by simultaneous noise and vibration.

The sound exposure level, L_{AE}, which is defined in Appendix 2, was employed to evaluate the noise stimuli. Appendix 5.1 discusses the various methods currently in use for evaluating noise. The effect of frequency, duration and intensity of noise on the reaction to noise stimuli is considered.

5.2 APPARATUS

Experiments 3 and 4 were conducted in a representation of a small sitting-room. Subjects sat on a contoured wooden seat, with their feet resting on a stationary footrest. The seat was secured to a vibrator table and was constrained to move in the vertical (z-axis) direction only. A Derritron VP30 electromagnetic vibrator, powered by a 300 watt amplifier drove the seat. A stationary wooden backrest was slightly contoured for comfort.

The acceleration time history of the vibration stimulus presented in the two experiments was frequency weighted to compensate for the frequency response of the vibrator-subject combination (see Section 3.2.3). The vibration received by the subjects was measured by an accelerometer positioned under the centre of the seat. Computer generated vibration stimuli were used as the input to the vibrator amplifier via a 10 bit digital-to-analogue converter and an eight pole Butterworth low-pass filter at 100 Hz (48 dB per octave roll off). The digital-to-analogue and digital-to-analogue sampling rate was 512 samples per second.

Noise stimuli were generated by two 100 watt Tannoy Mercury loudspeakers via an amplifier and noise reduction system. The loudspeakers were situated behind a curtain in front of the subject.

Section 3.2 provides full details of the apparatus, generation of the vibration and noise stimuli and the performance of the vibrator.

5.3 STIMULI

Experiments 3 and 4 involved the presentation to subjects of both the noise and the vertical (z-axis) vibration recorded simultaneously inside a house during the passage of a nearby loaded iron-ore train. The duration of the stimuli was 24 seconds. The frequency range of the dominant noise was 20 to 5 kHz. Figures

5.1 to 5.4 show the time histories and the spectra of the two stimuli.

The noise and vibration were each presented at six different levels. For Experiment 3 the sound exposure levels were 59, 64, 69, 74, 79 and 84 dB(A), with peak root-mean-square levels of 48, 53, 58, 63, 68 and 73 dB(A) respectively. For Experiment 4, the sound exposure levels were 54, 64, 69, 74 and 79 dB(A), with peak root-mean-square levels of 43, 48, 53, 58, 63 and 68 dB(A) respectively. The vibration dose values for Experiments 3 and 4 were 0.07, 0.10, 0.14, 0.20, 0.28 and 0.40 $ms^{-1.75}$, with W_b weighted (see BS 6841, 1987) root-mean-square acceleration, averaged over the 24 second duration, of 0.020, 0.030, 0.040, 0.060, 0.090 and 0.125 ms^{-2}. The original magnitude of the vibration stimulus recorded in the house was a vibration dose value of 0.11 $ms^{-1.75}$ (as in Figures 5.1 and 5.3). The range of magnitudes presented in Experiments 3 and 4 was therefore between 0.64 and 3.64 times the original magnitude.

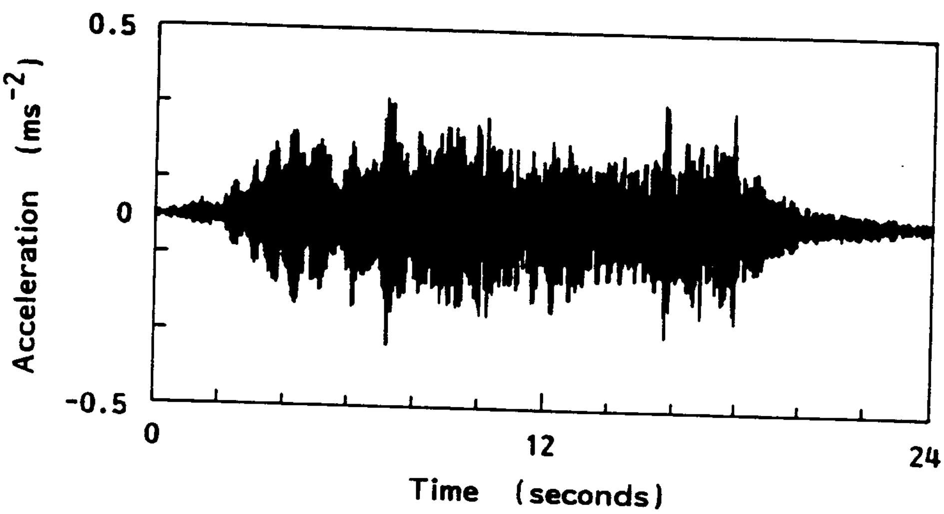

Figure 5.1 Vertical acceleration time history of the vibration stimulus (VDV = 0.11 $ms^{-1.75}$).

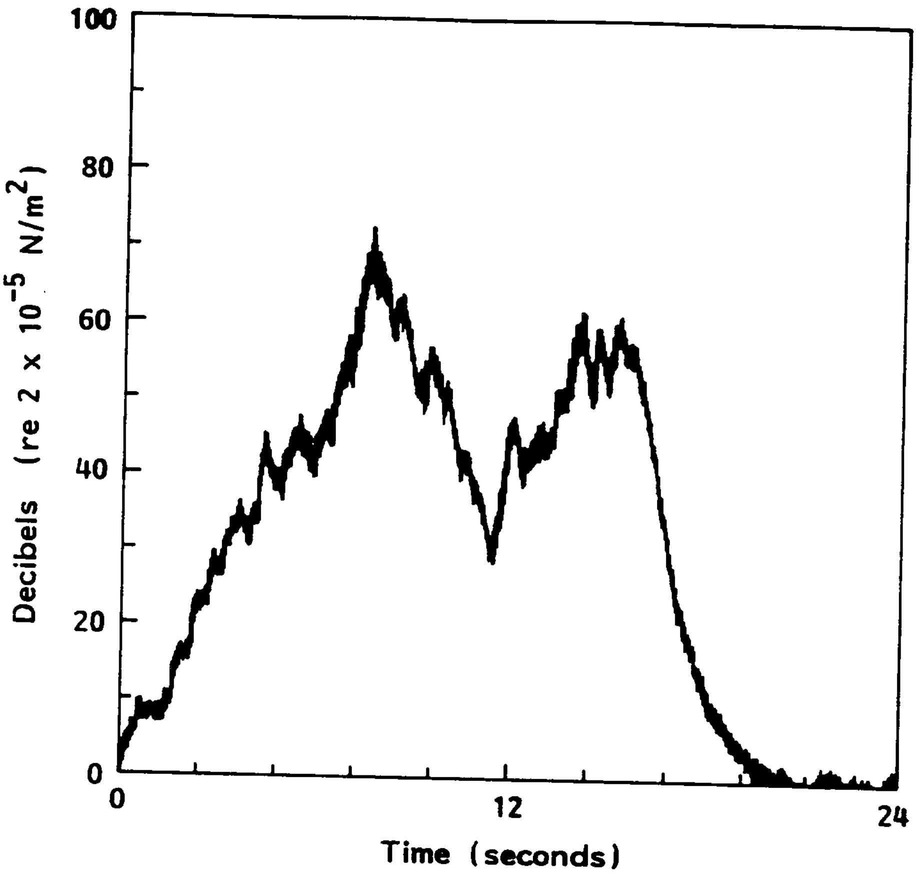

Figure 5.2 Sound pressure level time history of the noise stimulus (L_{AE} = 79 dB(A)).

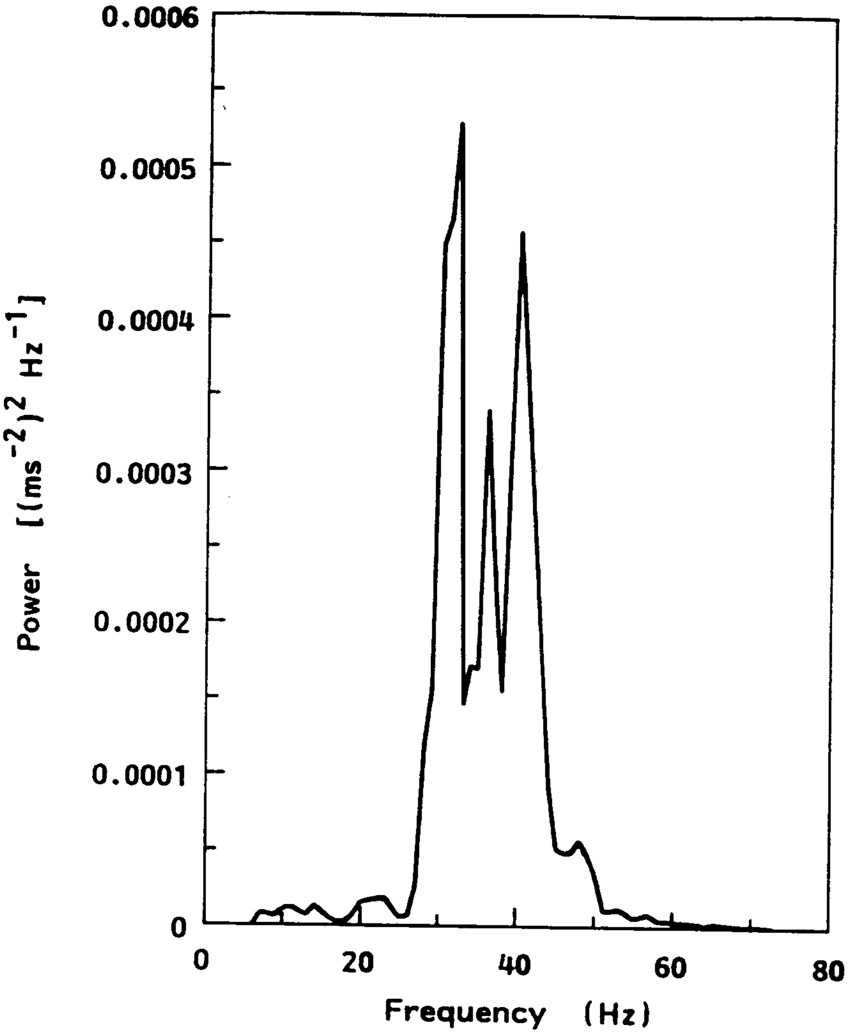

Figure 5.3 Acceleration power spectral density of vibration stimulus. Resolution 1 Hz, degrees of freedom 94 (VDV = 0.11 $ms^{-1.75}$).

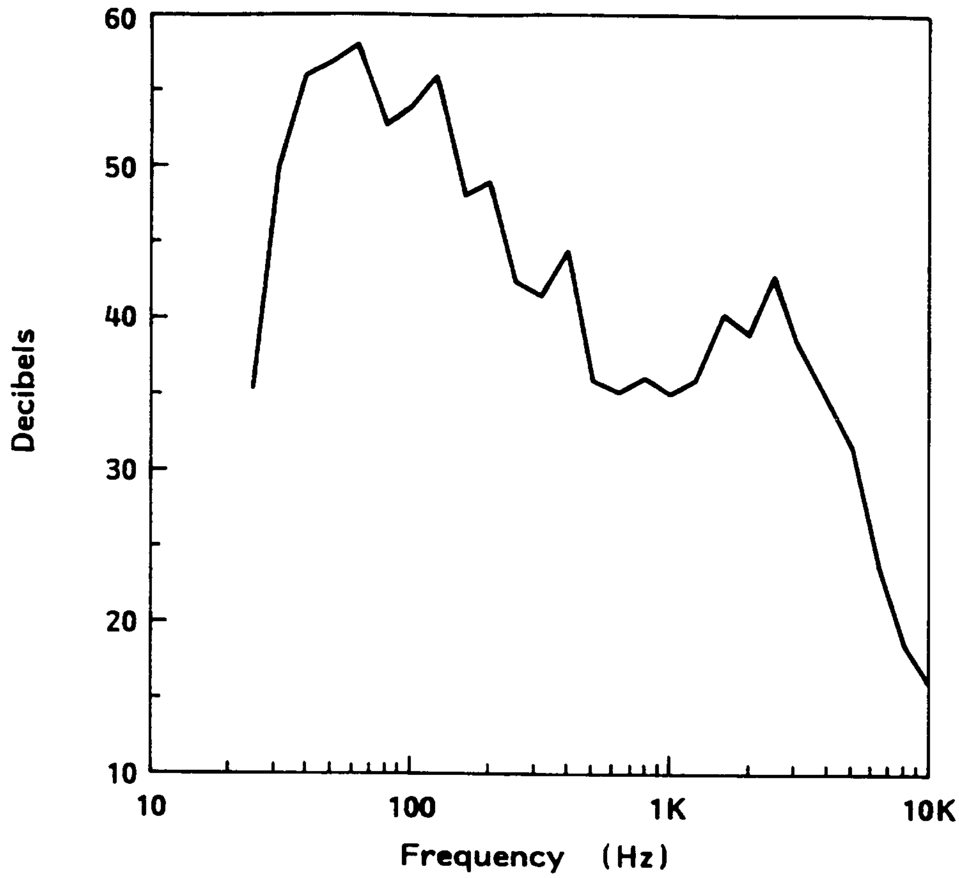

Figure 5.4 Spectrum of noise stimulus, 1/3–octave band levels.

5.4 EXPERIMENT 3: THE RELATIVE IMPORTANCE OF NOISE AND VIBRATION FROM RAILWAYS

5.4.1 Introduction

Experiment 3 was conducted to determine the subjective equivalence of noise and vibration and therefore the relative importance of the two stimuli. A small number of studies have been conducted to investigate the subjective equivalence of noise and vibration, e.g. Hempstock and Saunders (1972, 1973), Clarke and Oborne (1975a), Fleming and Griffin (1975) and Kjellberg, Wikstrom and Dimberg (1985). These studies were compared in Section 2.6 which showed that there is some agreement between the findings of previous studies at high magnitudes of vibration. However, only Hempstock and Saunders (1973) exposed subjects to vibration at low magnitudes which might occur in buildings. To establish the relative importance of railway noise and low magnitudes of vibration produced by passing trains further work is required.

The levels of noise and vibration which produce equal reaction may be described in terms of the vibration dose value, VDV, and the sound exposure level, L_{AE}, by an expression of the form:

$$L_{AE} = \frac{n_V}{n_S} \log_{10} VDV + k$$

where n_v is the vibration exponent in the psychophysical power function
n_s is the sound exponent
k is a constant.

The results of Experiment 3 were employed to derive such an expression for the subjective equivalence of noise and vibration. Thirty subjects were exposed to 36 presentations of simultaneous noise and vibration, consisting of paired combinations of six levels of noise and six magnitudes of vibration. Subjects indicated whether they would prefer the noise or vibration to be reduced. The responses were employed to determine the relative importance of the two stimuli. The findings should help to decide whether the reduction of noise or the reduction of vibration would be more likely to reduce the complaints from combined noise and vibration from railways.

5.4.2 Experimental Method

5.4.2.1 Subjects

Fifteen men and fifteen women aged between 16 and 60 years acted as paid subjects in Experiment 3. Prior to being exposed to stimuli, the subjects were shown a list of medical conditions which might have rendered them unfit for participation in the experiment (BSI, 1973).

5.4.2.2 Procedure

The subjects were instructed to sit on a wooden seat attached to the vibrator table in a comfortable upright posture. The feet and upper legs of each subject were positioned horizontally and the lower legs vertically by means of a stationary footrest. Before the start of the experiment, which continued for 30 minutes, the subjects were provided with the instructions shown in Appendix 5.2. All possible 36 paired combinations of six levels of noise and six magnitudes of vibration were presented in a different random order to each subject. After each presentation, the subjects were asked to say which of two stimuli, noise or vibration, they would prefer to be reduced, if they were to occur together in their own sitting-room. A simple seven-point scale was then employed to indicate the total annoyance produced by the combination of noise and vibration.

5.4.3 Results

The responses of the subjects were employed to determine the percentage of subjects objecting more to noise or to vibration at given levels. Table 5.1 shows the number of subjects who indicated a preference for the reduction of noise at each level of noise and vibration. Figure 5.5 illustrates the relation, for each magnitude of vibration, between the percentage of subjects preferring the noise to be reduced and the sound exposure level, L_{AE}. Figure 5.5 was used to construct the 25th, 50th and 75th percentiles shown in Figure 5.6. The percentiles indicate the combination of noise and vibration levels resulting in 25%, 50% and 75% of the subjects preferring noise to be reduced. The 50th percentile may be considered to indicate the noise and vibration levels which are subjectively equivalent to the average subject.

		L_{AE} (dB(A))					
		N_1 59	N_2 64	N_3 69	N_4 74	N_5 79	N_6 84
VDV ($ms^{-1.75}$)	V_1 0.07	20	29	30	30	30	30
	V_2 0.10	18	26	27	29	30	30
	V_3 0.14	7	17	20	28	30	30
	V_4 0.20	4	8	16	24	26	30
	V_5 0.28	0	1	8	15	22	29
	V_6 0.40	0	0	3	7	17	29

Table 5.1 The number of subjects indicating a preference for the reduction of noise.

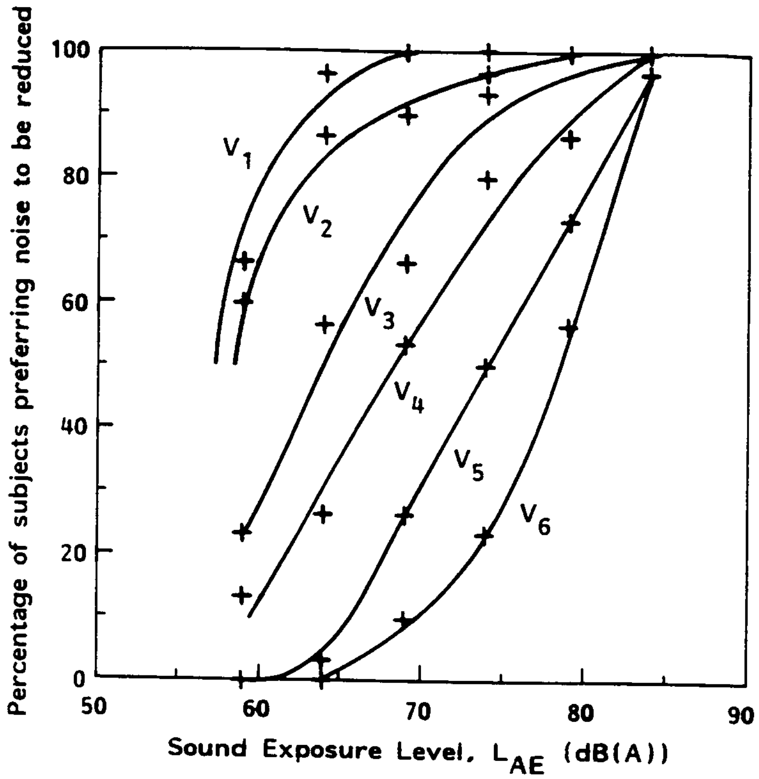

Figure 5.5 Percentage of subjects indicating a preference for the reduction of noise. Curves fitted by eye.

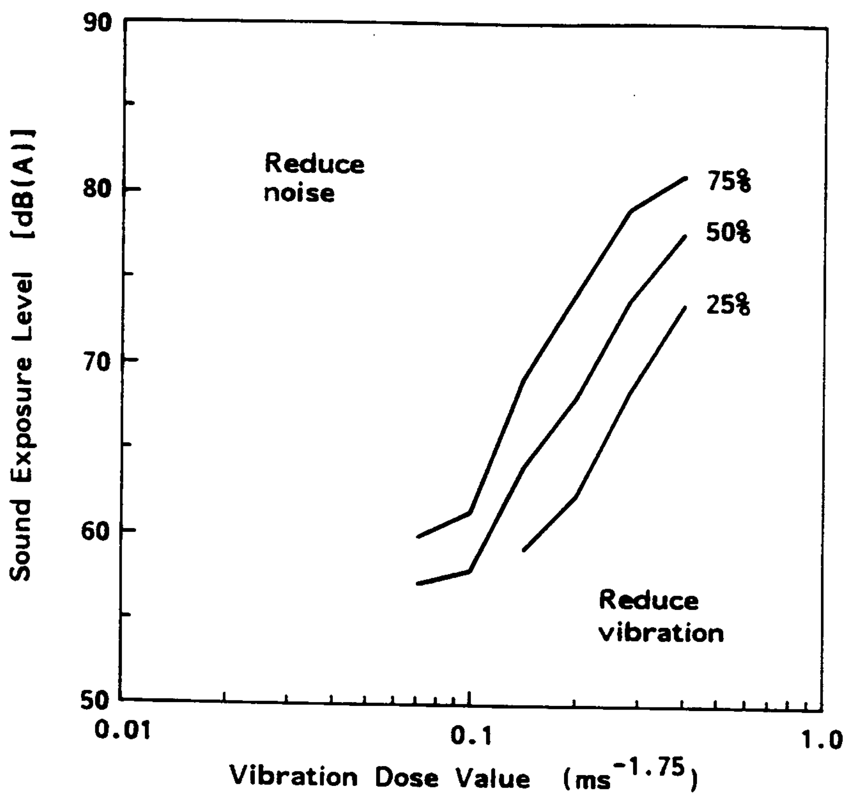

Figure 5.6 The 25th, 50th and 75th percentiles for the preference of reduction of noise.

The mean annoyance ratings of the 30 subjects for the 36 combinations of noise and vibration are shown in Table 5.2. The mean ratings were used to construct Figures 5.7 and 5.8. These figures illustrate graphically the effect of noise and the effect of vibration on the total annoyance due to the simultaneous combination of noise and vibration.

		L_{AE} (dB(A))					
		N_1 59	N_2 64	N_3 69	N_4 74	N_5 79	N_6 84
VDV ($ms^{-1.75}$)	V_1 0.07	1.77	2.23	3.00	3.90	4.70	5.37
	V_2 0.10	2.03	2.53	3.17	4.03	4.77	5.40
	V_3 0.14	2.40	2.73	3.13	3.93	4.80	5.37
	V_4 0.20	2.73	3.07	3.30	4.10	4.73	5.40
	V_5 0.28	3.37	3.13	3.73	4.20	4.77	5.30
	V_6 0.40	3.90	3.93	4.17	4.43	4.90	5.47

Table 5.2 Mean annoyance ratings for 30 subjects.

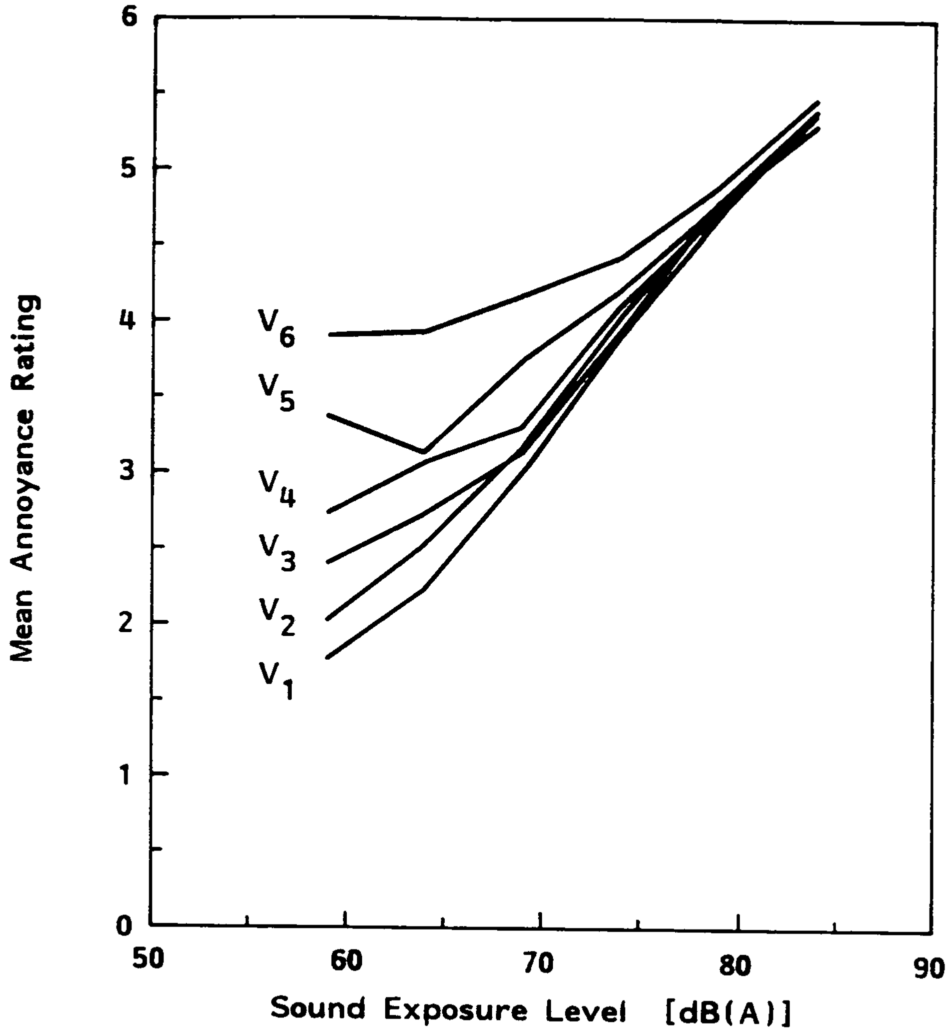

Figure 5.7 The effect of noise on the annoyance due to combined noise and vibration.

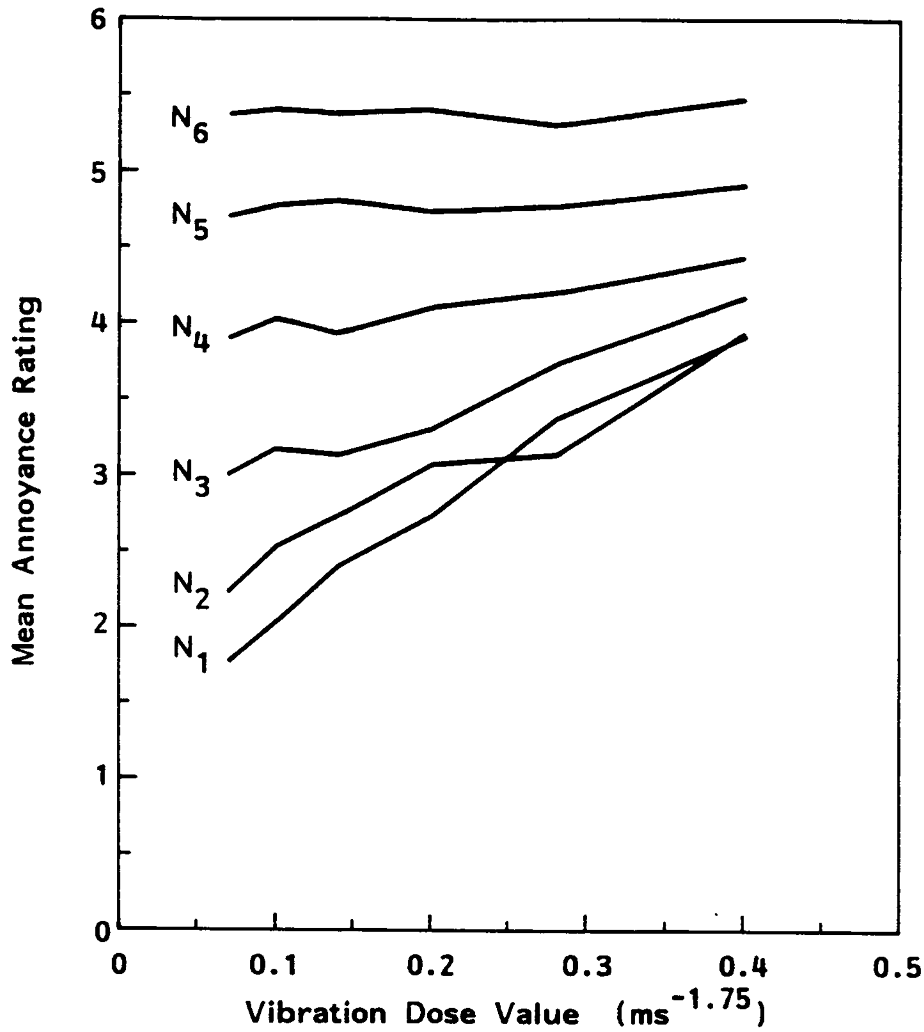

Figure 5.8 The effect of vibration on the annoyance due to combined noise and vibration.

5.4.4 Discussion and Conclusions

Figure 5.5 shows the percentage of subjects preferring noise to be reduced as a function of the sound exposure level for each of the six vibration magnitudes. At low vibration magnitudes the noise dominated and a high percentage of subjects preferred noise to be reduced. A smaller percentage of subjects preferred noise to be reduced at high vibration magnitudes.

Figure 5.7 illustrates the influence of noise on the annoyance at each vibration magnitude. The influence of vibration on the annoyance at each noise level is shown in Figure 5.8. The figures indicate that when noise and vibration occur together, the annoyance depended on both stimuli. In Figure 5.7 the slope of each curve decreases as the vibration increases, suggesting that an increase in noise had less effect on the annoyance rating at higher magnitudes of vibration.

Similarly, Figure 5.8 suggests that an increase in vibration had less effect on the annoyance rating at high levels of noise than at low levels of noise. This effect may be caused by the most annoying of the stimuli tending to dominate the overall response. However, the effect could also have been due to the subjects' responses being restricted to the range zero to six.

A study by Fleming and Griffin (1975) employed a similar technique to that employed in this experiment to investigate the subjective equivalence of a 1 kHz pure tone sound and 10 Hz sinusoidal whole-body vertical vibration. Their results were presented graphically as a subjective equivalence curve for noise level (dB SPL) and vibration magnitude (ms^{-2} r.m.s.). In Figure 5.9 their results have been converted to vibration dose values and sound exposure levels and compared to the results of the present study. The stimuli employed by Fleming and Griffin were of greater magnitude and of very different type to those used in the present study. However, it can be seen from the figure that the slopes of the two lines are very similar. If the two lines were extrapolated, the levels of noise and vibration considered to be equivalent would be similar in the two studies.

The figure may be employed to determine which of the two stimuli, noise or vibration, is more annoying when they occur together. If a combination of noise and vibration falls to the left of the equivalence curve, a reduction of noise would be more beneficial. If a combination of noise and vibration falls to the right of the equivalence curve, a reduction of vibration is more likely to be effective in reducing complaints from such a combination.

Linear regression analysis of the 50th percentile for the preference of reduction of noise showed that the subjective equality between the two stimuli is expressed by:

$$L_{AE} = 29.3 \log_{10} VDV + 89.2$$

For the study by Fleming and Griffin (1975) the relation is given by:

$$L_{AE} = 33.0 \log_{10} VDV + 93.6$$

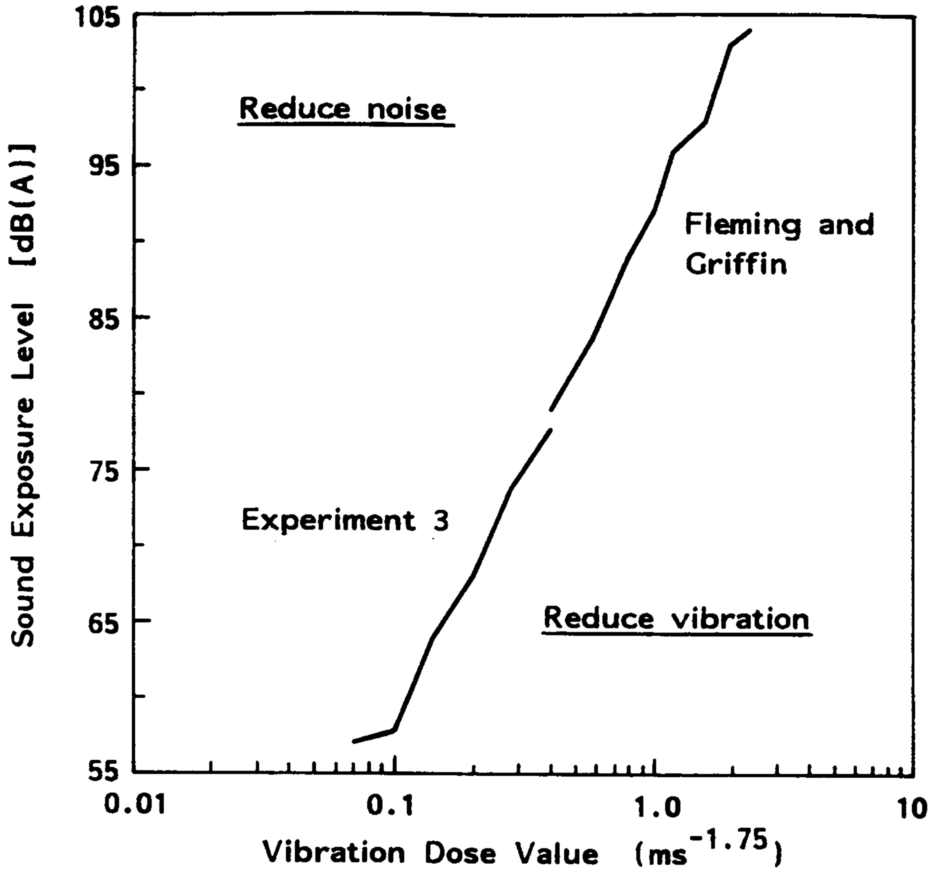

Figure 5.9 Comparison of equivalence curves from Experiment 3 and from Fleming and Griffin (1975).

Section 2.6 compared the results of several studies which investigated the subjective equivalence of noise and vibration. A study was conducted by Hempstock and Saunders (1973) in which subjects attended two sessions. In one session, subjects altered the magnitude of a vibration stimulus to be subjectively equivalent to a fixed noise stimulus. In a second session subjects adjusted a noise stimulus to a level which caused the same reaction as a fixed vibration stimulus. The authors described the equivalence between noise and vibration, determined by averaging the results of the two sessions, in terms of the sound pressure level and the root-mean-square acceleration. Further analysis of their data provides a relation in terms of the vibration dose value, VDV, and the sound exposure level, L_{AE}, which is given by:

$$L_{AE} = 30.3 \log_{10} VDV + 82.0$$

In a study conducted by Kjellberg, Wikstrom and Dimberg (1985) subjects adjusted broad band noise to a level which gave rise to the same discomfort as vibration recorded in forklift trucks. Further analysis of the results reported by Kjellberg et al provides the following expression for the subjective equivalence of noise and vibration:

$$L_{AE} = 40.0 \log_{10} VDV + 75.5$$

Figure 5.10 compares the equivalence curve determined from the results of Experiment 3 with the equivalence curves of Hempstock and Saunders (1973), Fleming and Griffin (1975) and Kjellberg et al (1985). The curve of Experiment 3 compares most similarly with the curve of Fleming and Griffin (1975) which employed the same experimental method.

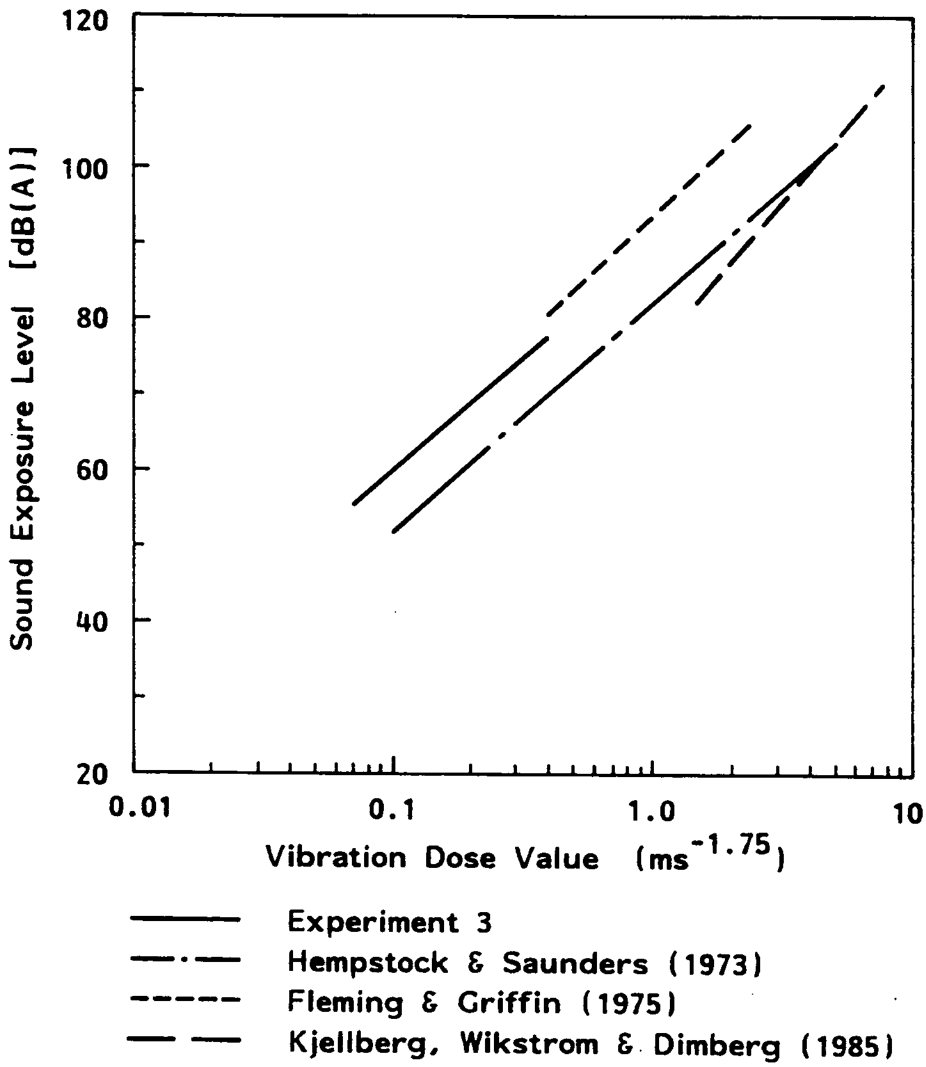

Figure 5.10 Comparison of equivalence curves from Experiment 3 and from previous studies.

5.5 EXPERIMENT 4: THE INTERACTION AND COMBINED EFFECTS OF NOISE AND VIBRATION FROM RAILWAYS

5.5.1 Introduction

Experiment 4 was conducted to investigate the interaction between responses to simultaneously presented noise and vibration and the combined effects of the two stimuli. The experiment sought to answer the following questions:

(i) Is a judgement of vibration influenced by the presence of noise?

(ii) Is a judgement of noise influenced by the presence of vibration?

(iii) How can the annoyance due to noise and vibration be summed to give a total measure of annoyance?

Section 2.7 described in detail previous studies of the reaction to simultaneous noise and vibration. Sandover (1970), Miwa and Yonekawa (1973) and Dempsey, Leatherwood and Drezek (1976) investigated the influence of the presence of one stimulus on the assessment of the other. Sandover found that the judgements of pure tones in the frequency range 125 Hz to 4 kHz were reduced by the presence of vibration for 125 Hz sound only. Miwa and Yonekawa found evidence that reaction to vibration was reduced by the presence of noise. Dempsey et al also reported some evidence of an influence of the presence of one stimulus on the assessment of the other stimulus. However, previous investigations are few and further work is required to answer questions (i) and (ii).

Section 2.7 reviewed nine studies which were conducted to investigate the overall response to simultaneous noise and vibration. Of these, seven proposed or tested a relation to predict the combined effects of the two stimuli. Only two studies fully described the derivation of the relation (Innocent and Sandover (1972), Leatherwood (1979)). Additional investigations are necessary to quantify the combined effects of noise and vibration and hence to answer question (iii) above.

In this experiment, 24 subjects attended three sessions during each of which they were presented with six levels of noise combined with six magnitudes of vibration in all 36 combinations. The method of magnitude estimation was employed to rate the annoyance caused.

5.5.2 Experimental Method

5.5.2.1 Subjects

Twelve men and twelve women aged between 17 and 60 years acted as paid subjects in the experiment. All subjects were shown a list of medical conditions, before the start of the experiment, which would have rendered them unfit for participation in the experiment (BSI, 1973).

5.5.2.2 Procedure

The subjects attended three sessions, each of which lasted 45 minutes. Session A investigated the assessment of vibration in the presence of noise; subjects assigned values to indicate their reaction to the vibration. Session B investigated the assessment of noise in the presence of vibration; subjects assigned values to indicate their reaction to noise. Session C investigated the combined effects of noise and vibration. Assigned values were based on the response to the combination of noise and vibration. The subjects attended the three sessions in a balanced random order. The method of magnitude estimation was employed. Each subject practised using this technique, at the beginning of the first session, by assigning numbers to lines according to their length (Appendix 5.3).

For Session A, the subjects were instructed to assign a number to each stimulus to indicate the annoyance caused by the vibration. They were asked to make the ratio between the numbers assigned correspond to the ratio between the annoyance caused by each vibration stimulus. For the first stimulus received by the subjects, the annoyance caused by the vibration was assigned the value of 100. This stimulus consisted of noise and vibration at sound exposure level 64 dB(A) and vibration dose value 0.14 $ms^{-1.75}$. The subjects then received four practice stimuli with different levels of noise and vibration and they assigned a number to each stimulus. The subjects were provided with an opportunity to ask questions before starting the experiment, which again began with the stimulus previously assigned the value of 100. This was followed by 42 stimuli: all 36 combinations of the six levels of noise and the six magnitudes of vibration, plus the six magnitudes of vibration without noise. The instructions for Session A are shown in Appendix 5.4.

For Session B, the subjects were instructed to assign a number to each stimulus to indicate the annoyance caused by the noise. The procedure was the same as for

Session A. Subjects received four practice stimuli and then 42 stimuli consisting of 36 combinations of noise and vibration plus the six levels of noise without vibration. The instructions for Session B are shown in Appendix 5.5.

For Session C, the subjects were instructed to assign numbers to each stimulus to indicate the annoyance caused by the combination of noise and vibration (Appendix 5.6). The subjects were presented with four practice stimuli and then 48 stimuli consisting of 36 combinations of noise and vibration, six magnitudes of vibration without noise and six levels of noise without vibration.

For each session and each subject the stimuli were presented in a different random order. The practice stimuli and the stimulus assigned the value of 100 were the same for all three sessions and all subjects.

5.5.3 Results

Appendix 5.7 shows the median responses for each session. The first stimulus for each session (L_{AE} = 64 dB(A), VDV = 0.14 $ms^{-1.75}$), which was assigned the value of 100, was presented again to each subject during the session and was assigned a value by the subjects. The median value assigned to this stimulus was 100. This indicates a consistency in the subjects' responses over the duration of each session.

The median responses for the assessment of vibration (Session A) are presented as a function of vibration magnitude (VDV) in Figure 5.11 and as a function of noise level (L_{AE}) in Figure 5.12. The figures show some evidence that at low magnitudes of vibration, the annoyance due to vibration was reduced by high levels of noise. In contrast, at high magnitudes of vibration, the annoyance increased at high levels of noise.

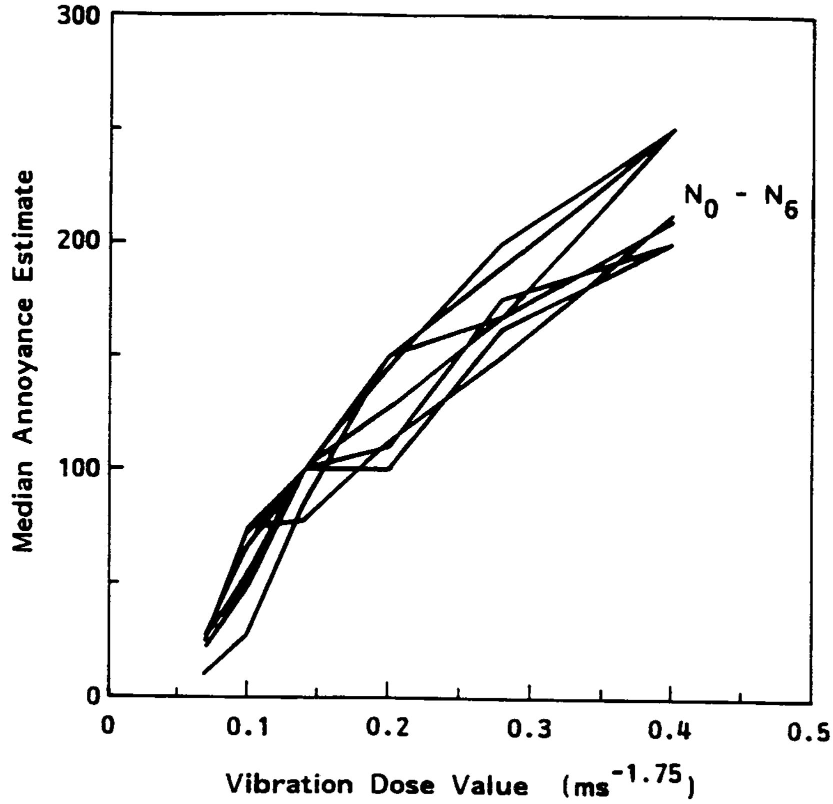

Figure 5.11 The assessment of vibration as a function of vibration magnitude (Session A).

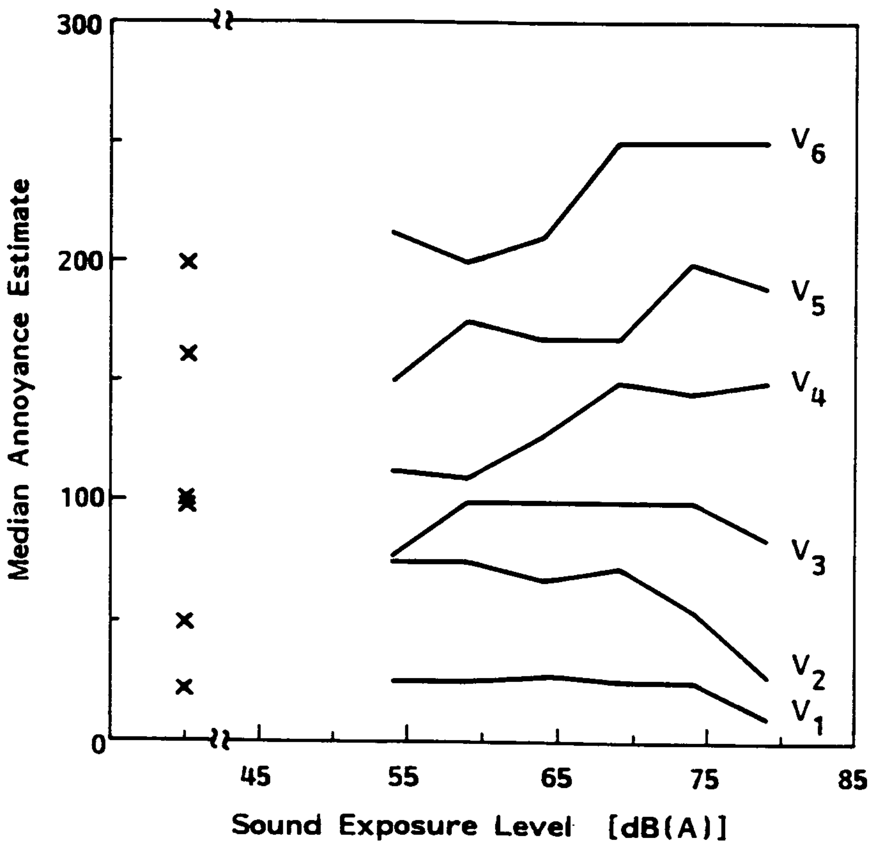

Figure 5.12 The influence of noise level on the assessment of vibration (Session A). X = no noise stimulus.

The median values assigned for the assessment of noise (Session B) are shown in Figure 5.13 as a function of vibration magnitude (VDV) and as a function of noise level (L_{AE}) in Figure 5.14. The figures indicate little change in the assessment of noise with increasing vibration magnitude.

The median results for the combined effects of noise and vibration (Session C) are illustrated as a function of vibration magnitude in Figure 5.15 and as a function of noise level in Figure 5.16. The results of Session C were employed to determine a relation to describe the total annoyance from combinations of noise and vibration. Sessions A and C involved conditions in which vibration alone was presented. The median magnitude estimates obtained from these conditions, as a function of the sound exposure level, are shown separately as crosses in Figures 5.12 and 5.16. The crosses correspond to background noise or to the absence of a noise stimulus. The background noise cannot be quantified in terms of the sound exposure level since it was continuous. Therefore, in the figures, the results obtained from conditions with vibration alone are not shown to correspond to specific sound exposure levels. For these conditions, the noise levels, φ_s, (where $\log_{10} \varphi_s = L_{AE}$ dB(A)) were approximated by a value of zero in the regression analysis (see Section 5.5.4) i.e. when there was no noise:

$$\psi_s = k\varphi_s^{ns}$$

$$= 0$$

where ψ_s is the annoyance caused by the noise

φ_s is the objective magnitude of the noise

n_s is the exponent for noise

k is a constant.

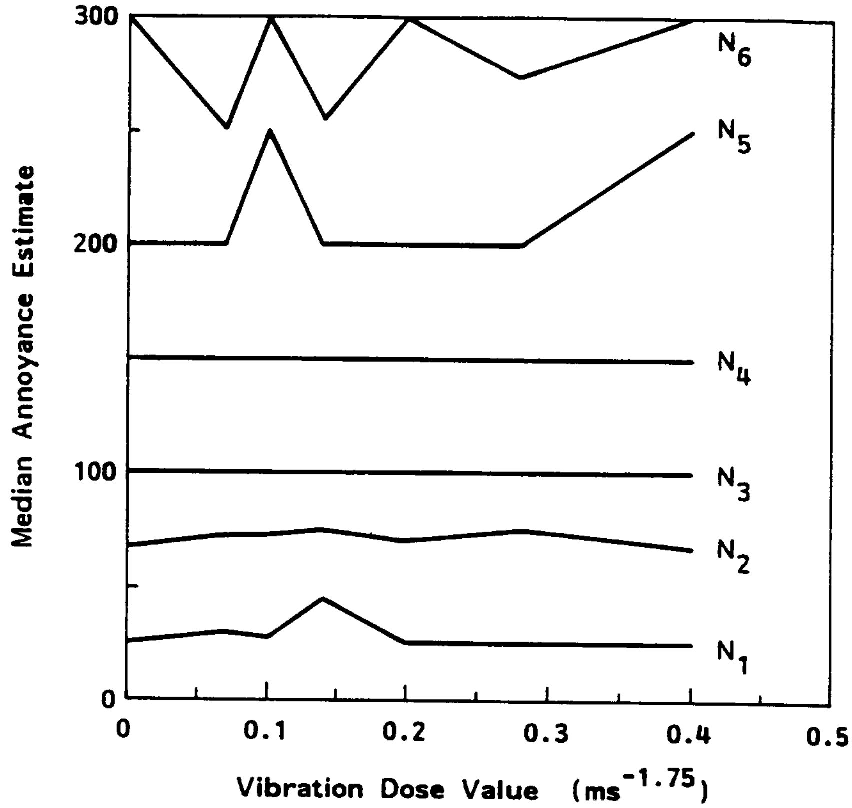

Figure 5.13 The influence of vibration magnitude on the assessment of noise (Session B).

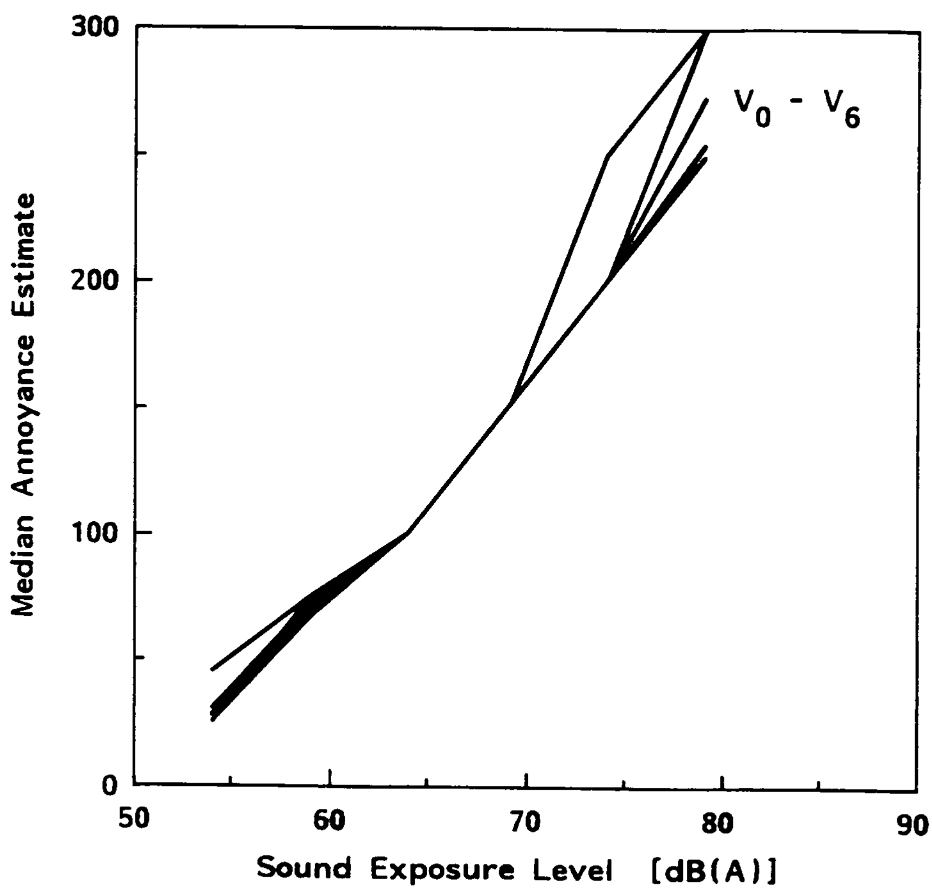

Figure 5.14 The assessment of noise as a function of noise level (Session B).

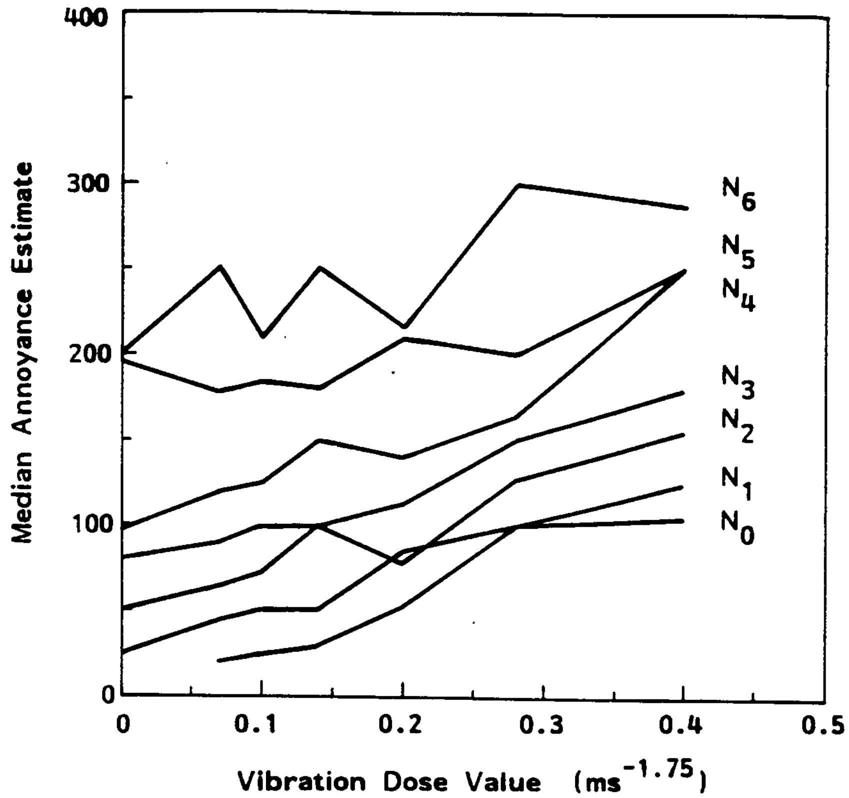

Figure 5.15 The assessment of noise and vibration as a function of vibration magnitude (Session C).

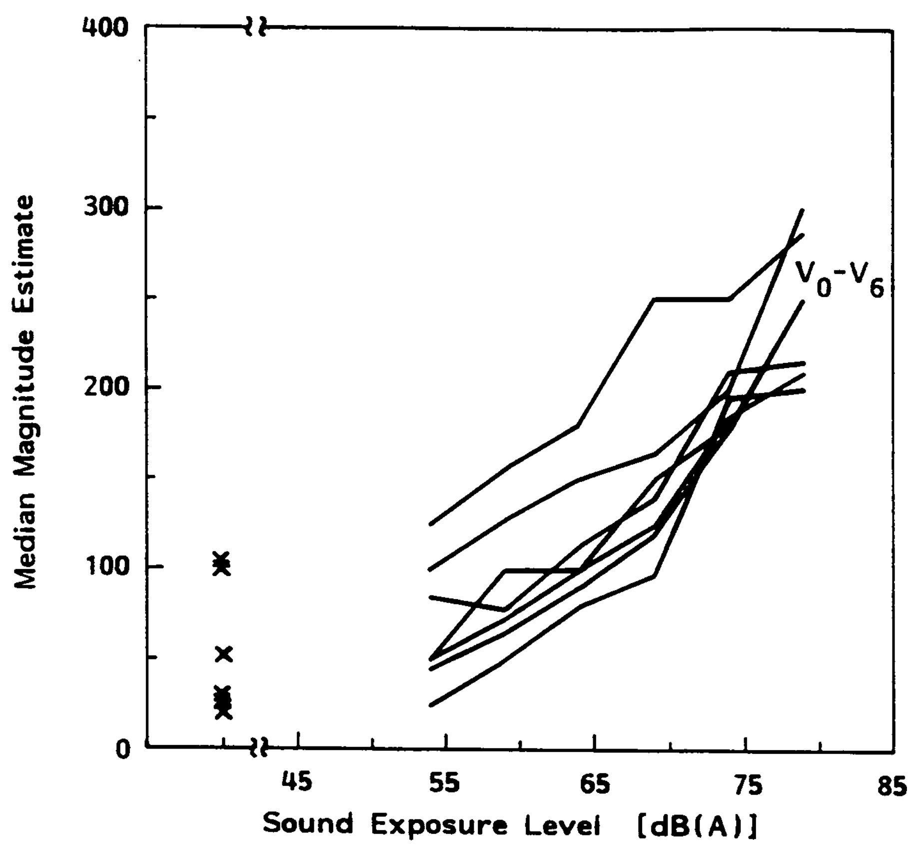

Figure 5.16 The assessment of noise and vibration as a function of noise level (Session C). X = no noise stimulus.

5.5.4 Discussion and Conclusions

The results for the assessment of vibration, shown in Figure 5.12, suggest that there was a tendency for the assessment of vibration to decrease at high levels of noise when the vibration magnitude was small, but to increase at high levels of noise when the vibration magnitude was large. This result suggests that at low magnitudes of vibration there was an antagonistic effect, whereby the presence of noise reduced the assessment of vibration, while at high magnitudes of vibration there was a synergistic effect where the presence of noise increased the annoyance due to vibration. Friedman two-way analysis of variance test was applied to the results from Session A to determine whether the presence of noise had a significant effect on the assessment of vibration. The test was applied at each vibration magnitude to test for a difference between the annoyance caused by vibration at the six noise levels. The presence of noise had a significant effect ($p < 0.05$) at all vibration magnitudes except at V_3 (VDV = 0.14 $ms^{-1.75}$) and at V_5 (VDV = 0.28 $ms^{-1.75}$).

Friedman two-way analysis of variance test was applied to the results from Session B to determine whether the presence of vibration had a significant effect on the assessment of noise. The test was applied at each noise level to test for a difference between the annoyance due to noise at the six vibration magnitudes. The presence of vibration had no significant effect ($p > 0.05$) at any of the noise levels. This result is illustrated in Figure 5.14 which shows little difference in the median annoyance ratings at the six vibration magnitudes.

Linear regression analysis was carried out on those results from Session C when the subjects were presented with either noise alone or vibration alone. Thus, a relation was obtained between the subjective response, ψ, and the magnitude of the stimuli, φ, of the form:

$$\log \psi = n \log \varphi + \log k$$

where n and k are constants. The relation is usually expressed as a power function i.e. $\psi = k\varphi^n$.

For Session C when the subject received noise alone, the relation was given by:

$$\log_{10} \psi_s = 0.039 \log_{10} \varphi_s - 0.663 \qquad (5.1)$$

where $\log_{10} \varphi_s = L_{AE}$ (dB(A))

from which $\psi_s = 0.217 \varphi_s^{0.039}$

The correlation coefficient ($r = 0.83$) was highly significant ($p < 0.001$).

For the same session, the relation for vibration was given by:

$$\log_{10} \psi_v = 1.04 \log_{10} \varphi_v + 2.39 \qquad (5.2)$$

where φ_v = VDV ($ms^{-1.75}$)

from which $\psi_v = 245 \varphi_v^{1.04}$

The correlation ($r = 0.54$) was highly significant ($p < 0.001$).

Appendix 5.1 considers current evaluation methods for noise. Section A5.1.5 discusses previous studies conducted to investigate the dependence of loudness on noise intensity. Examination of available data by Stevens in 1955 suggested 10 dB changes in noise intensity corresponded to a loudness ratio of 2:1, i.e. the relation between the subjective magnitude of noise, ψ_s, and sound pressure level, SPL, is given by:

$$\log_{10} \psi_s = 0.030 \text{ SPL} + k$$

where k is a constant.

However, more recent data has accumulated to suggest 9 dB changes in noise intensity correspond to a loudness ratio of 2:1 (see Stevens, 1971), i.e. the relation is given by:

$$\log_{10} \psi_s = 0.033 \text{ SPL} + k$$

This is in broad agreement with the relation determined for the subjective response, ψ_s, and the noise level, φ_s, (Equation 5.1) which may be written as:

$$\log_{10} \psi_s = 0.039 \text{ SPL} + k$$

The value of the vibration exponent determined as 1.04 for the relation between the subjective response, ψ_v, and the vibration magnitude, φ_v, (Equation 5.2) compares well with the mean value of 1.1 determined in a study by Fothergill and Griffin (1977) and of 0.96 and 1.20 in a study by Hiramatsu and Griffin (1984), both of which also employed the method of magnitude estimation.

The values determined of the noise exponent, n_s, and the vibration exponent, n_v, were employed to predict the overall annoyance produced by combined noise and vibration. The assumption was made that the overall annoyance, ψ, may be approximated by a summation of the individual effects of the two stimuli and may be described by a relation of the form:

$$\psi = a + \psi_v + \psi_s$$

from which $$\psi = a + b\varphi_v^{nv} + c\varphi_s^{ns}$$

where a, b and c are constants. The equation was determined from multiple regression analysis of the subjective response, ψ, on two variables, $\varphi_s^{0.039}$ and $\varphi_v^{1.04}$. The analysis was carried out on the median response at each combination of noise and vibration for Session C. The resulting relation is given by:

$$\psi = 15.9 + 260\ \varphi_v^{1.04} + 0.167\ \varphi_s^{0.039} \qquad (5.3)$$

The correlation coefficient ($r = 0.97$) was highly significant ($p < 0.005$). Figures 5.17 and 5.18 show the predicted response as a function of the vibration dose value and the sound exposure level respectively.

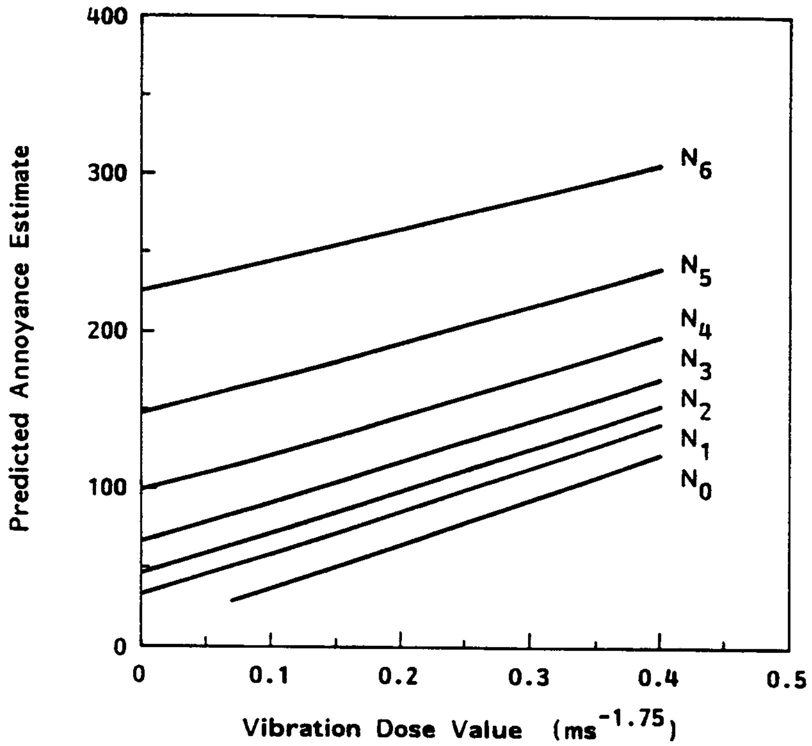

Figure 5.17 Predicted annoyance from combined noise and vibration as a function of the vibration magnitude (Equation 5.3).

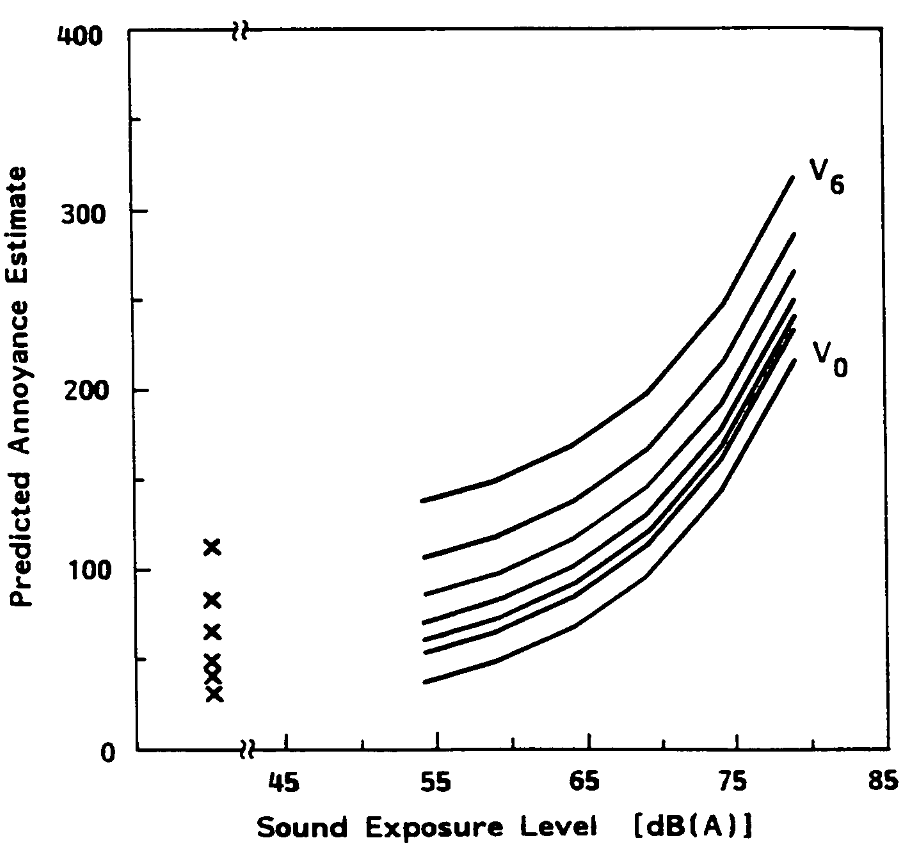

Figure 5.18 Predicted overall annoyance from combined noise and vibration as a function of the noise level (Equation 5.3). x = no noise stimulus.

A second prediction method was employed which included an interaction variable between the two stimuli. The equation determined from multiple regression analysis of ψ on three variables: $\varphi_s^{0.039}$, $\varphi_v^{1.04}$ and the interaction variable $\varphi_s^{0.039}$ $\varphi_v^{1.04}$, is given by:

$$\psi = 10.8 + 290\ \varphi_v^{1.04} + 0.178\ \varphi_s^{0.039} - 0.066\ \varphi_s^{0.039}\ \varphi_v^{1.04} \qquad (5.4)$$

The correlation coefficient ($r = 0.97$) was highly significant ($p < 0.005$). The interaction variable contributes very little to the predicted subjective magnitude, ψ, so the two prediction equations (5.3 and 5.4) are not significantly different. The addition of the interaction variable does not significantly improve the agreement between the predicted and median values.

Equation 5.3 and 5.4, describing the predicted disturbance from combined noise and vibration, can be employed to determine a relation for the subjective equivalence of noise and vibration. From the first prediction method (Equation 5.3) the subjective equality is given by:

$$L_{AE} = 26.7 \log_{10} VDV + 81.7$$

From the second prediction method (Equation 5.4) the relation is given by:

$$L_{AE} = 26.7 \log_{10} VDV + 82.4$$

5.6 GENERAL DISCUSSION

In Figure 5.19 the subjective equivalence curve obtained from Experiment 3 is compared with the curve from the studies by Fleming and Griffin (1975), Hempstock and Saunders (1973), Kjellberg et al (1985) (see Section 2.6) and with the line evolved from the first prediction method (Equation 5.3) in Experiment 4.

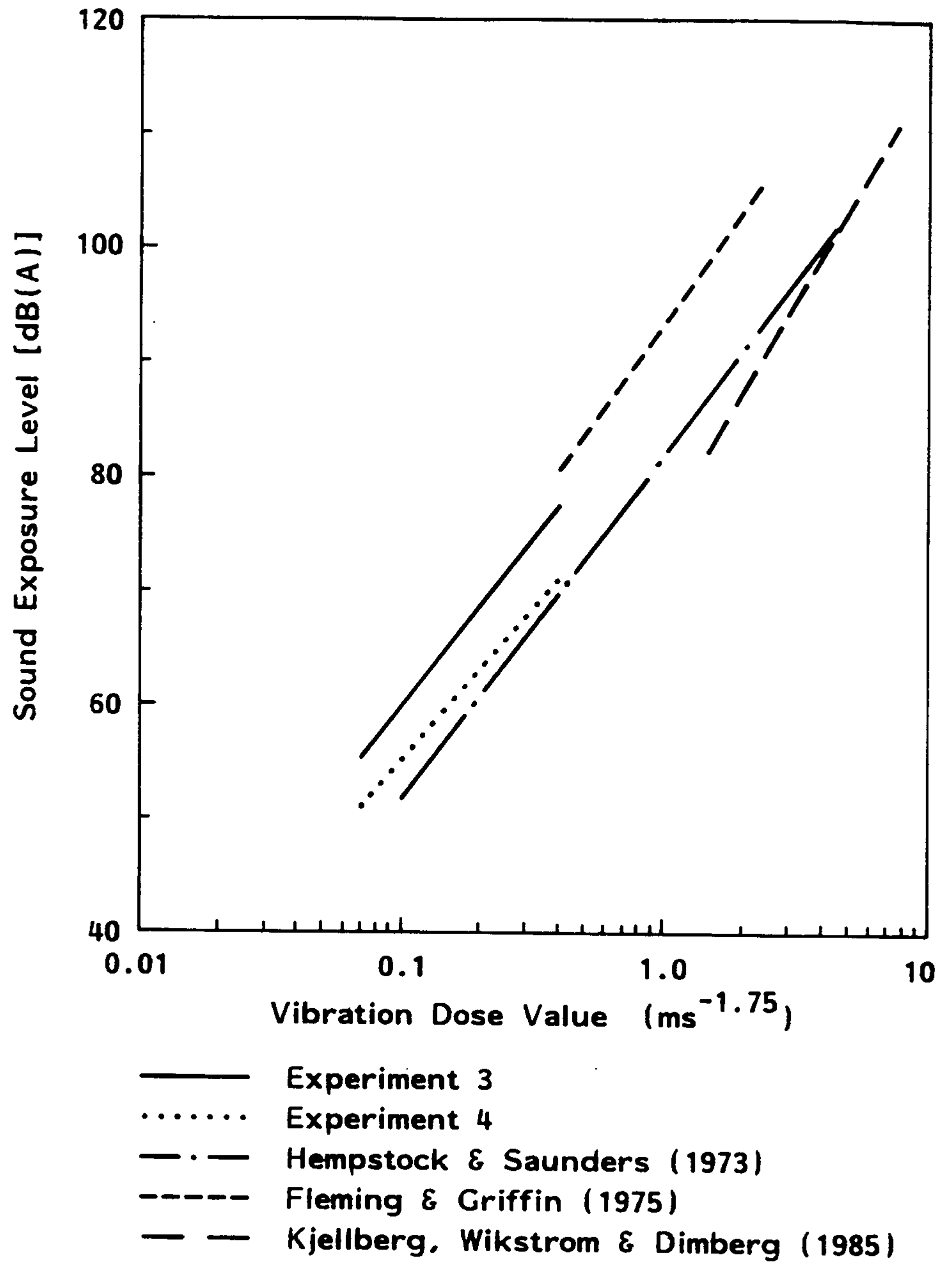

Figure 5.19 Comparison of subjective equivalence curves from Experiments 3 and 4 and from previous studies.

The subjective equivalence curve obtained from the results of Experiment 3 gives noise levels equivalent to vibration which are about 6 dB greater than the equivalence curve from Experiment 4. This difference may be partly a result of different stimuli ranges. The noise levels of the stimuli employed in Experiment 4 (L_{AE} = 54 to 79 dB(A)) were 5 dB less than for Experiment 3 (L_{AE} = 59 to 84 dB(A)). If the subjects had a tendency to normalise their response this would lower the curve for Experiment 4 by 5 dB. An effect of this type was exposed by Garner (1959) with the method of ratio estimation. Garner believed that differences in the results of experiments on judgements of loudness may have been partly attributable to context effects. Garner claimed ability to train different groups of subjects to state that the half-loudness of a 90 dB tone was either 60, 70 or 80 dB depending on the range of intensities available to each group as a choice of half-loudness. This tendency for subjects to regress towards the mean is often known as the regression effect.

The gradient of the equivalence curve corresponds to the ratio of the exponents in the power functions (n_v/n_s). Since the value of n_v is usually unity and the value of n_s is approximately 0.033, the gradient of the equivalence curve should be about 30. The gradient of the equivalence curve of Experiment 4 (26.7) is less than the gradient of the equivalence curve of Experiment 3 (29.3). The difference in the gradients may be attributable to the regression effect. This effect may be described as a tendency for the subjects to shorten the range of whichever variable they are allowed to adjust. In the case of magnitude estimation, the adjustable variable is assigned a number. Thus, the regression effect is a tendency to avoid the use of very high and very low numbers. If the range of subjective magnitudes was greater for noise than for vibration, the result may have been to reduce the gradient of the equal annoyance curve. However, the difference in the gradients of the curve obtained from Experiments 3 and 4 may be considered small in view of the difference in the methods employed.

The equivalence curve obtained from studies by Hempstock and Saunders, Fleming and Griffin, and Kjellberg et al have similar gradients to the curves of Experiments 3 and 4 and therefore similar ratios of the exponents of noise and vibration. The gradients are in approximate agreement with the expected value of 30. The results of the study conducted by Hempstock and Saunders suggest equivalent levels of vibration and noise which are similar to the results of Kjellberg et al. These two studies both employed the method of cross-modality matching. Noise levels equivalent to higher vibration magnitudes were obtained from Experiment 3. Similar results were obtained from the study by Fleming and Griffin which employed the same experimental technique.

5.7 CONCLUSIONS

Subjectively equivalent levels of railway noise and railway-induced building vibration have been determined from the results of Experiment 3 which compare well with the equivalent levels for single frequency stimuli determined in a study by Fleming and Griffin (1975) which employed the same experimental technique. Differences between the equivalence lines from Experiments 3 and 4 and from previous studies may be attributed to differences in the range of noise levels and to different experimental techniques.

The results of Experiment 4 suggest that vibration does not influence the judgement of noise but that the judgement of vibration can be increased or reduced by the presence of noise, depending on the relative magnitudes of the two stimuli.

The results of the experiments have shown that when railway noise and railway-induced building vibration occur together the overall annoyance depends on the magnitudes of both stimuli. The results suggest that although there may be an interaction between the effects of the two stimuli, the effect may not be simple or consistent. A reasonable approximation of the annoyance with different levels of noise and vibration may be determined from a summation of the individual effects (Equation 5.3). The relation can be used to provide an estimate of the degree to which the overall annoyance may be reduced by a reduction in the vibration and/or noise levels.

CHAPTER 6

THE FREQUENCY DEPENDENCE OF SUBJECTIVE REACTION TO VERTICAL AND HORIZONTAL WHOLE-BODY VIBRATION AT LOW MAGNITUDES

6.1 INTRODUCTION

Vibration produced in buildings by passing trains occurs mainly in the translational axes with frequencies below about 80 Hz and at magnitudes comparable with the threshold of perception (Woodroof and Griffin (1987)). The objective assessment of building vibration requires knowledge of the relative disturbance produced by different frequencies, magnitudes, directions and durations of motion. This chapter describes Experiment 5 which was conducted to investigate the influence of three of these factors: vibration frequency, vibration magnitude and vibration direction.

Various experimenters have reported studies of the effects of the frequency dependence of vertical vibration on comfort, e.g. Miwa and Yonekawa (1971), Shoenberger and Harris (1971), Jones and Saunders (1972) and Griffin, Whitham and Parsons (1982). Comfort contours for horizontal motion have been determined less often than contours for vertical motion (e.g. Miwa and Yonekawa (1971) and Griffin, Whitham and Parsons (1982)). Although there are wide differences between the findings of the studies, there are also some agreements. Some differences may be attributed to the different experimental techniques employed in the various studies. (Griffin and Whitham (1976, 1980a) have shown that experimental procedures can significantly affect comfort contours.) Other differences may be a result of different postures and different types of seats. For example, Leatherwood et al (1980) employed compliant seats which may have modified the vibration transmitted to the subjects. The results of previous studies do not all support the frequency dependence of reaction to vertical whole-body vibration proposed in International Standard 2631 (1978). The British Standard, BS 6841 (1987), "Guide to the measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock", therefore defines a weighting more consistent with experimental data. Both standards imply that the frequency dependence of the threshold of perception is the same as the frequency dependence of subjective reaction to whole-body vibration at magnitudes greater than the perception threshold.

Section 2.5 reviewed the small number of studies which have determined perception thresholds and comfort contours in the same experiment. The aim of the review was to determine whether there is experimental evidence to show that the frequency weightings for high magnitude vibration may also be applied to low magnitude building vibration. Comparisons of equivalent comfort contours and perception thresholds for vertical vibration have been reported by Reiher and Meister (1931), Gorrill and Snyder (1957), Chaney (1964) and Miwa and Yonekawa (1971). The findings of these studies show little agreement on the effect of vibration magnitude on the frequency dependence of subjective response to whole-body vertical vibration. Only Reiher and Meister (1931) and Miwa and Yonekawa (1971) have reported studies in which both comfort contours and perception thresholds for horizontal vibration have been determined in the same experiment. Reiher and Meister (1931) reported that at low magnitudes sensitivity to acceleration was greatest at low frequencies, while at high magnitudes sensitivity was greatest at high frequencies. In contrast, results from the study by Miwa and Yonekawa suggested that the effect of frequency does not depend on the magnitude of vibration. Section 2.5 showed that there is insufficient experimental data available on which to judge whether frequency weightings for high magnitude vibration are appropriate for low magnitude vibration of the type which might occur in buildings during the passage of a nearby train.

The experiment reported in this chapter was conducted to determine the frequency dependence of subjective response to low magnitude vibration at frequencies between 4 Hz and 63 Hz. Reactions to various magnitudes of vertical and horizontal motion were determined by comparison with a reference sound stimulus. The use of a common reference stimulus enabled the subjective equivalence between vertical and horizontal motion to be determined. The psychophysical relation between subjective response, ψ, and objective magnitude, φ, was determined in the form of a power function, $\psi = k\varphi^n$, where k and n are constants. The analogy in psychoacoustics is the relation determined by Stevens (1955) to equate loudness, L, and sound pressure, p, as a power function $L = kp^{0.6}$. This experiment also provides information on the frequency and axis dependence of the exponent, n, in the power function.

6.2 APPARATUS

Vertical (z–axis) and horizontal (y–axis) whole–body vibration were produced separately by a one–metre stroke vertical hydraulic vibrator and a one–metre stroke horizontal hydraulic vibrator. The subjects sat on a rigid wooden seat secured to one of the vibrator platforms. Although rigid, the seat was slightly contoured so as to reduce the pressure on the ischial tuberosities. The feet and thighs of each subject were positioned horizontally and the lower legs vertically by means of an adjustable, stationary footrest. There was no backrest; subjects wore a loose lap–belt for safety purposes. Accelerometers secured to the wooden seat measured its z–axis or y–axis motion. The vibration stimuli were frequency weighted to compensate for the frequency response of the vibrator–subject combination (see Section 3.3.2). Computer generated vibration stimuli were used as the input to the vibrator amplifier via a 10 bit digital–to–analogue converter and an eight pole Butterworth low–pass filter at 100 Hz (48 dB per octave roll off). The digital–to–analogue and analogue–to–digital sampling rates were 400 samples per second.

A Bruel and Kjaer noise generator was used to produce the sound stimulus which was presented to subjects (via a Bruel and Kjaer $^1/_3$–octave band filter set and an amplifier system) by 1.5 cm diameter Koss KMP/2 miniature earphones fitted with removable sponge covers and positioned at the entrance to the auditory canals. Subjects wore Bilsom Viking 2318 circumaural ear defenders over the miniature earphones to reduce extraneous noise. Calibration of the earphones was conducted by use of a Kemar artificial eardrum.

Section 3.3 provides full details of the apparatus, generation of the vibration and noise stimuli and the performance of the vibrators.

6.3 EXPERIMENTAL METHOD

6.3.1 Stimuli

The vibration stimuli consisted of sinusoidal motion which increased and decreased in magnitude in a manner similar to vibration induced in a building by a passing train. This involved a linear increase in amplitude from zero for 2 seconds, followed by a constant amplitude for 5 seconds and then a linear decrease in amplitude to zero for 3 seconds. For each axis of motion, nine frequencies were investigated in the range 4 Hz to 63 Hz at $\frac{1}{2}$–octave intervals (4.0, 5.6, 8.0, 11.3, 16.0, 22.5, 31.5, 44.5 and 63.0 Hz). Each frequency was presented at six magnitudes with root-mean-square accelerations of 0.04, 0.06, 0.10, 0.16, 0.25 and 0.40 ms^{-2} averaged over the 10 second duration. Section 3.3 provides the background noise and vibration magnitudes, cross-axis coupling and distortion figures.

The reference sound stimulus was $^1/_3$-octave band noise centred at 1 kHz at a sound pressure level of 70 dB for 5 seconds (A-weighted sound exposure level, L_{AE} = 77 dB).

6.3.2 Procedure

Experiment 5 employed the method of magnitude estimation in which all vibration stimuli were compared with the five second noise stimulus. Each subject attended two sessions which lasted 40 minutes. One session investigated the frequency dependence of subjective reaction to vertical (z-axis) whole-body vibration and the other session investigated the frequency dependence of subjective reaction to horizontal (y-axis) whole-body vibration. The experimental designs of the two sessions were identical.

Ten men and ten women aged between 22 and 61 years acted as paid subjects in the experiment. All subjects were shown a list of medical conditions which would have rendered them unfit for participation in the experiment (BSI, 1973). Five men and five women first attended the session which involved exposure to vertical motion while the remaining subjects commenced with horizontal motion. Between five and ten days elapsed between the two sessions.

Prior to beginning the first session, each subject was given practice at using the method of magnitude estimation by assigning numbers to lines according to their length (Appendix 6.1). The subjects were then presented with the reference noise stimulus followed by four practice vibration stimuli and given an opportunity to ask questions before starting the experiment. The subjects were instructed to sit in a comfortable upright posture. The instructions are shown in Appendix 6.2.

Fifty-four vibration stimuli, consisting of all combinations of nine frequencies and six magnitudes, were presented in a different random order to each subject in each session. The noise stimulus was repeated before every group of four vibration stimuli and was indicated as corresponding to a subjective magnitude of 100. The subjects were instructed to assign a number to each vibration stimulus so as to indicate the annoyance, as a multiple of the annoyance caused by the noise.

A digital computer was used to generate the vibration stimuli, to determine and store the overall r.m.s. acceleration of each stimulus and to store each magnitude estimate. The actual magnitudes of the z-axis stimuli differed from the expected magnitudes at low magnitudes and low frequencies due to the non-linear response of the vibrator. Analysis of the results therefore involved the measured acceleration magnitudes of all stimuli. The background vibration was measured at the end of each session.

6.4 RESULTS

Figures 6.1 and 6.2 show the median magnitude estimate, ψ, as a function of the mean acceleration, φ, (log-log co-ordinates) for each frequency of vertical (z-axis) and horizontal (y-axis) motion. A relation between magnitude estimate, ψ, and acceleration magnitude, φ, was determined in the form $\psi = k\varphi^n$ for each frequency and axis by linear least squares regression. The resulting regression curves are also shown. Tables 6.1 and 6.2 give the values of the exponent, n, and the product moment correlation coefficient, r, for the regression equation at each frequency of z-axis and y-axis motion. The correlations were all significant at the $p < 0.01$ level, except 4 Hz horizontal motion for which the correlation was significant at the $p < 0.05$ level.

For z-axis motion there was no significant difference between the gradients of the regression lines for different frequencies. For y-axis motion, the gradients were significantly different ($p < 0.01$) (Test for homogeneity of several independent values of b, Edwards, 1976). On the basis of these results, statistical analysis was conducted between all pairs of frequencies for horizontal motion (Test of null hypothesis that $\beta_1 - \beta_2 = 0$, Edwards, 1976). The levels of significance of the differences between the regression coefficients are shown in Table 6.3.

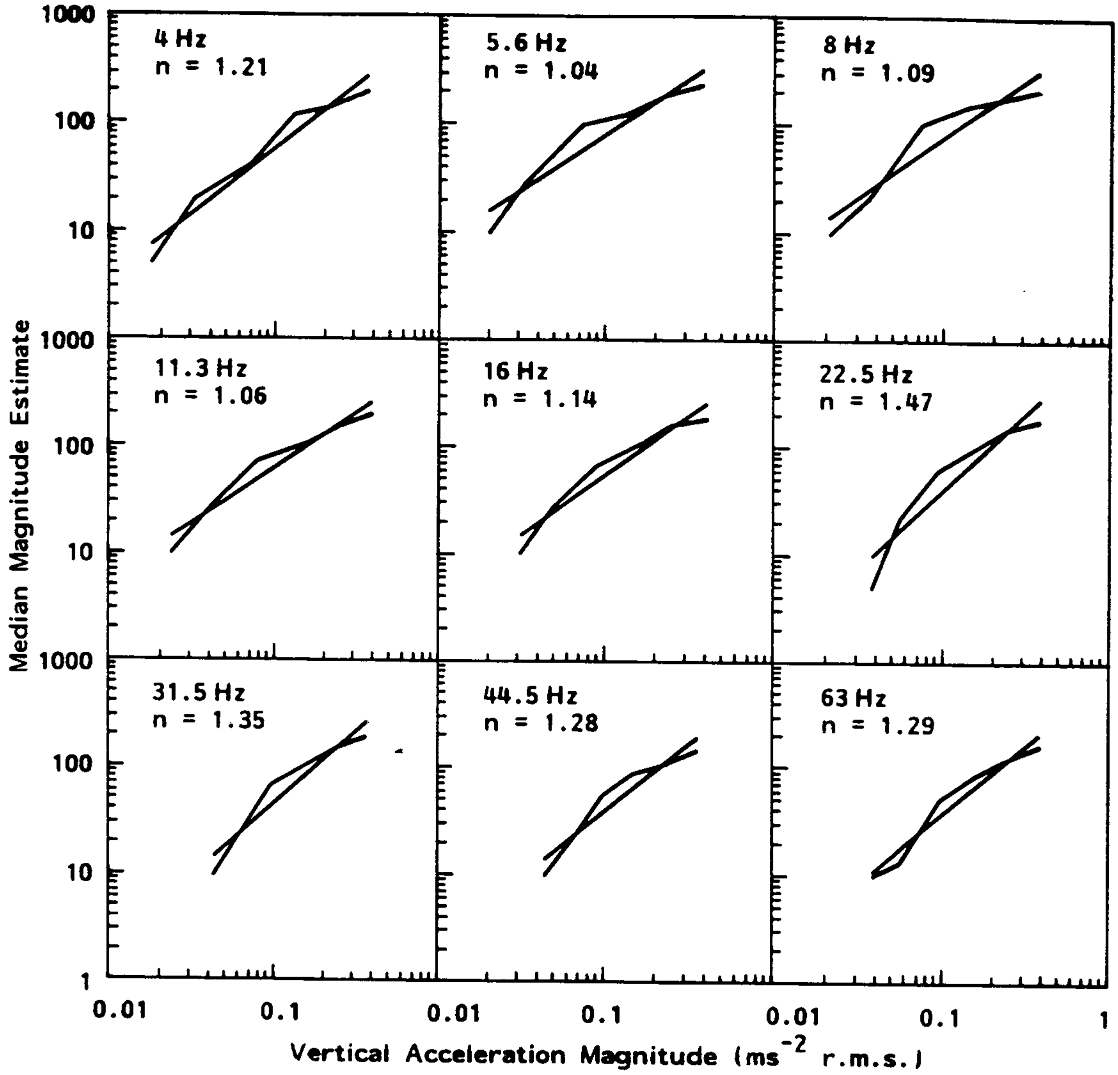

Figure 6.1 Median magnitude estimate, ψ, as a function of vertical (z-axis) acceleration magnitude, φ ($\psi = k\varphi^n$).

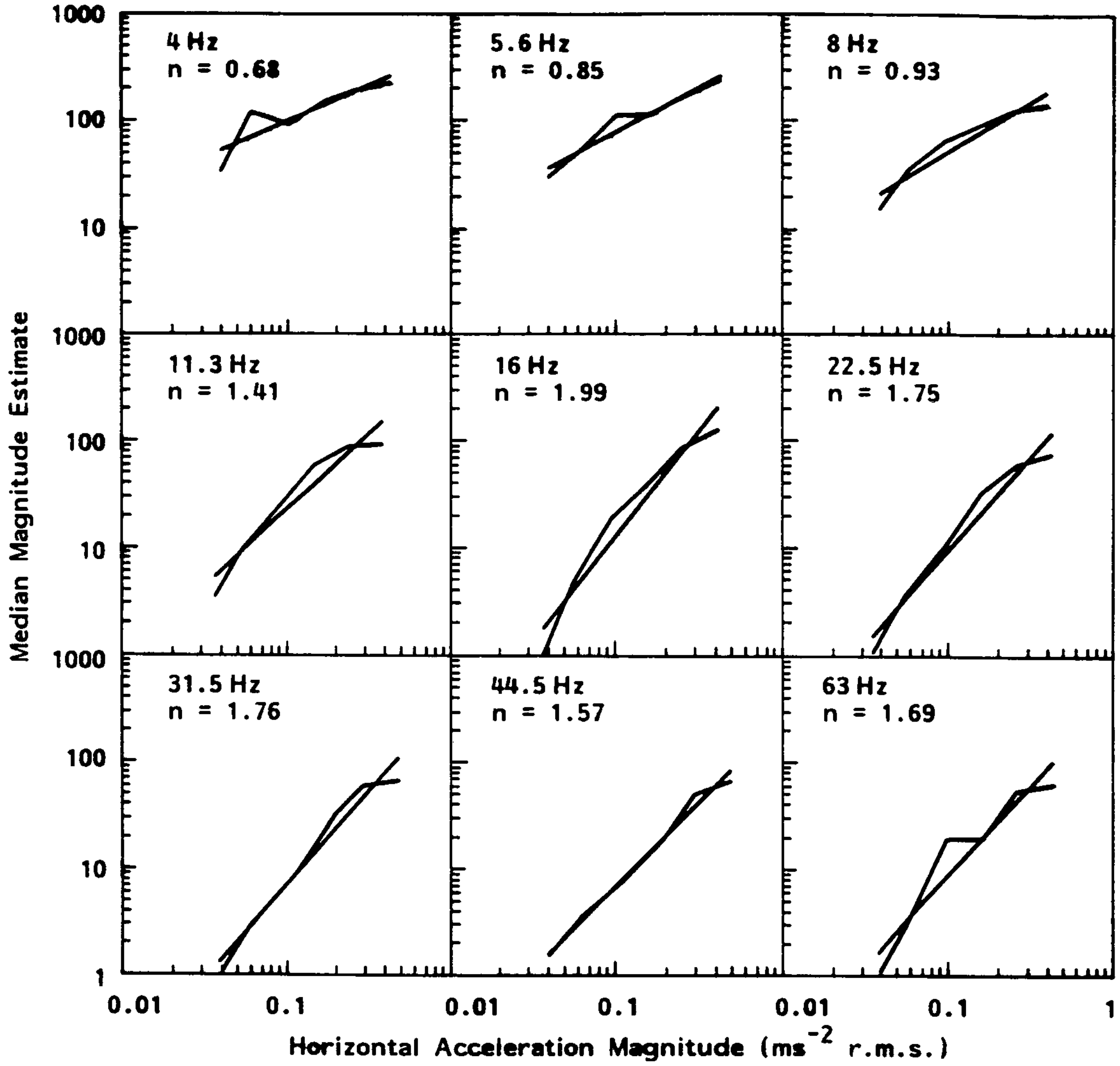

Figure 6.2 Median magnitude estimate, ψ, as a function of horizontal (y-axis) acceleration magnitude, φ ($\psi = k\varphi^n$).

Frequency Hz	Exponent n_z	Product Moment Correlation Coefficient r
4.0	1.21	0.974
5.6	1.04	0.955
8.0	1.09	0.945
11.3	1.06	0.971
16.0	1.14	0.968
22.5	1.47	0.941
31.5	1.35	0.960
44.5	1.28	0.960
63.0	1.29	0.975

Table 6.1 Regression and correlation coefficients for vertical motion.

Frequency Hz	Exponent n_y	Product Moment Correlation Coefficient r
4.0	0.68	0.878
5.6	0.85	0.971
8.0	0.93	0.957
11.3	1.41	0.961
16.0	1.99	0.973
22.5	1.75	0.979
31.5	1.76	0.983
44.5	1.57	0.994
63.0	1.69	0.950

Table 6.2 Regression and correlation coefficients for horizontal motion.

		Frequency (Hz)								
		4.0	5.6	8.0	11.3	16.0	22.5	31.5	44.5	63.0
Frequency (Hz)	4.0		-	-	*	***	***	***	***	*
	5.6			-	***	***	***	***	***	*
	8.0				-	***	**	**	***	*
	11.3					-	-	-	-	-
	16.0						-	-	-	-
	22.5							-	-	-
	31.5								-	-
	44.5									-
	63.0									

-	Not significant
*	$p < 0.05$
**	$p < 0.01$
***	$p < 0.005$

two-tailed test

Table 6.3 Significance of differences between gradients of regression lines for different frequencies of horizontal motion.

By substitution into the regression equations of the six acceleration magnitudes presented to the subjects (0.04 to 0.40 ms^{-2} r.m.s.), weighting functions were determined for each vibration magnitude employed in the experiment. Figures 6.3 and 6.4 indicate that the shape of the weighting functions for horizontal motion are much more magnitude dependent than the weightings for vertical motion.

The use of the same reference noise stimulus in the two sessions provided a means of comparing the response to vertical and horizontal motion. Figure 6.5 shows frequency weightings for vertical and horizontal motion obtained by averaging over the six magnitudes of vibration. The frequency weightings are plotted on the same graph to illustrate the relative disturbance from the two axes of motion. The results indicate that for frequencies greater than 5 Hz, vertical motion caused more annoyance than horizontal motion.

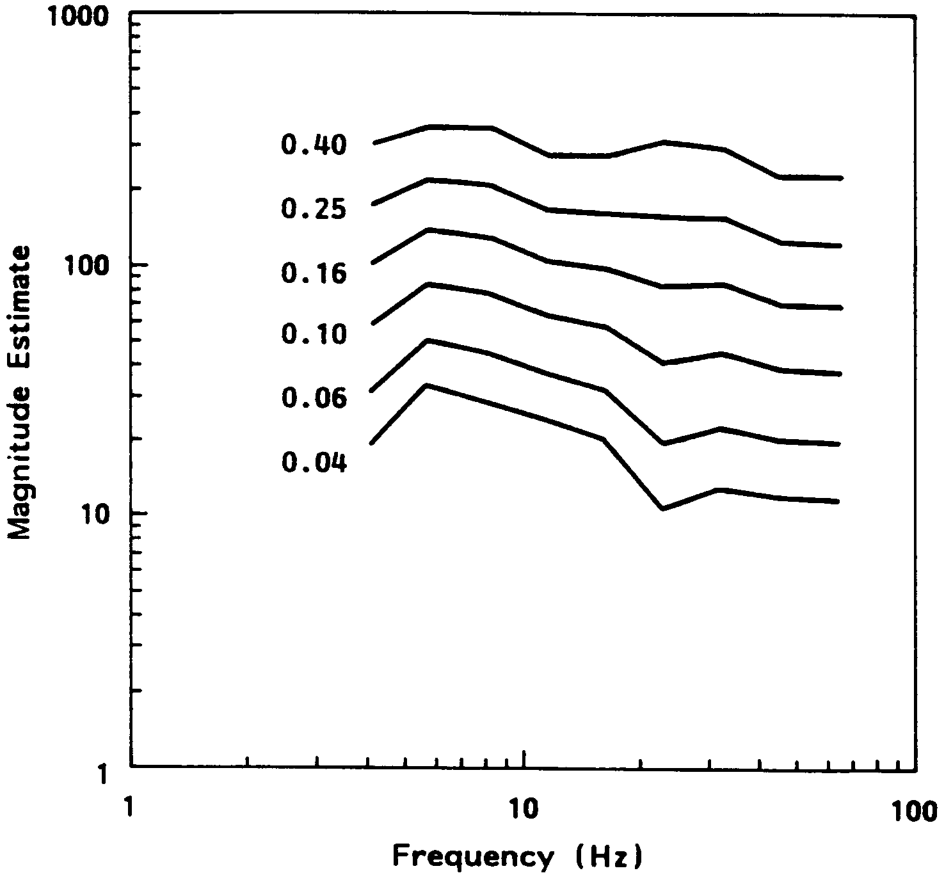

Figure 6.3 Vertical (z-axis) frequency weightings corresponding to six acceleration magnitudes (0.04 to 0.40 ms^{-2} r.m.s.).

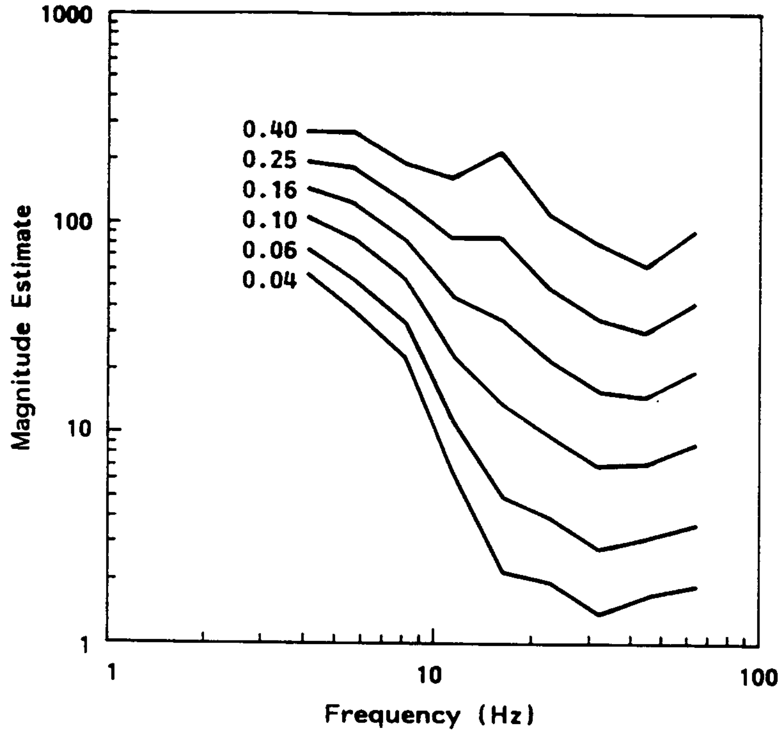

Figure 6.4 Horizontal (y-axis) frequency weightings corresponding to six acceleration magnitudes (0.04 to 0.40 ms^{-2} r.m.s.).

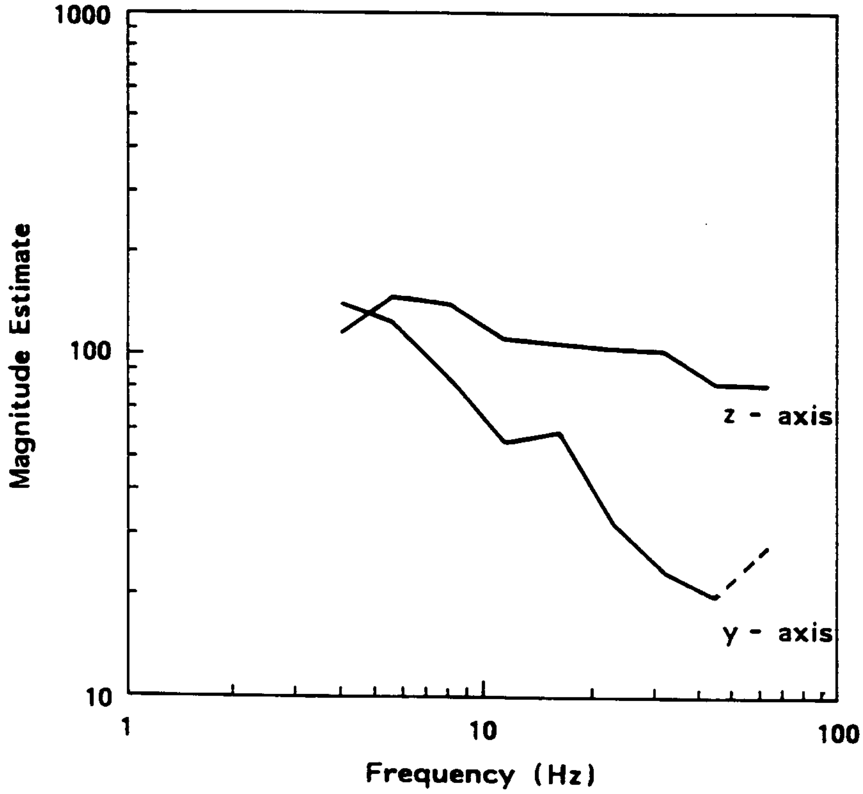

Figure 6.5 Vertical (z-axis) and horizontal (y-axis) frequency weightings averaged over all magnitudes. Horizontal weightings above 50 Hz are tentative.

6.5 DISCUSSION

The relation between magnitude estimate, ψ, and acceleration magnitude, φ, determined in power law form, $\psi = k\varphi^n$, resulted in exponents, n, at each frequency varying from 1.04 to 1.47 for vertical motion and from 0.68 to 1.99 for horizontal motion. The mean value of the exponent, averaged over all frequencies, was 1.21 for vertical motion and 1.40 for horizontal motion. These values are similar to the vibration exponent of 1.04 determined in Experiment 4 (see Section 5.5). The values are also similar to those from other studies, which have indicated that an exponent of unity is reasonably appropriate for vertical vibration. Jones and Saunders (1974) found an average growth function of 0.93. Clarke and Oborne (1975a) compared magnitude estimation and magnitude production techniques which resulted in exponents of 0.93 and 1.17 respectively. Fothergill and Griffin (1977) also compared magnitude estimation and magnitude production and found exponents of 1.12 and 1.64.

Statistical analysis of the present study showed that for y–axis motion the exponent was dependent on vibration frequency. Other studies have shown little evidence of a frequency dependence for the exponent in the power law describing the effect of magnitude of whole–body vibration. Miwa and Yonekawa (1971) determined the exponent for vertical motion and for horizontal motion at 5, 20 and 60 Hz and found no difference between the exponents at the three frequencies. Jones and Saunders (1974) exposed subjects to vertical vibration in the frequency range 5 Hz to 80 Hz. The results indicated an effect of frequency between only a few pairs of frequencies. Shoenberger and Harris (1971) investigated subjective response to vertical vibration at seven frequencies in the range 3.5 to 20 Hz. The exponent at each frequency varied between 0.86 and 1.04 – a small variation compared with intersubject variability.

It is evident from Figures 6.1 and 6.2 that the experimental data form curves on the log–log co–ordinates, with a steeper slope at low magnitudes. The curve is apparent in the results for both horizontal and vertical motion. Other studies which have investigated the relation between subjective magnitude, ψ, and objective magnitude, φ, at a number of vibration frequencies show little evidence of a curved relationship on log–log co–ordinates (see Miwa and Yonekawa (1971), Shoenberger and Harris (1971), Clarke and Oborne (1975a) and Hiramatsu and Griffin (1984)). However, these studies generally investigated motions at substantially higher magnitudes than the present study. A similar effect was found by Galanter and Messick (1961) in a study in which they investigated the relation between noise level and perceived loudness. They reported a failure of low level noise stimuli to conform to the psychoacoustic power law: when the noise stimuli were at similar levels to the ambient noise level, the slope of the loudness function became steeper.

The slope of the regression line relating magnitude estimate and acceleration magnitude increased as the frequency of motion increased and the effect was more marked for horizontal motion. The average gradient of the horizontal regression lines was near unity and similar to the findings of other studies conducted at higher magnitudes. However, at low frequencies, where subjective magnitudes were similar to other studies, the gradient was substantially less than unity. It is possible that the increase in the slope with frequency was an effect of magnitude rather than of frequency. The same acceleration magnitudes were presented at each frequency but the subjective magnitudes at low frequencies were greater than the subjective magnitudes at high frequencies. Greater slopes (higher values of the exponent, n) at high frequencies may have arisen from lower subjective magnitudes which fall on the steeper section of the curve.

Some horizontal stimuli at high frequencies and low magnitudes were not felt by some subjects so they responded with very small magnitude estimates. The median magnitude estimates were employed in the regression analysis so the results were not affected unless a large number of subjects found stimuli imperceptible. Regression analysis was repeated with the removal of stimuli not felt by more than six of the 20 subjects (stimuli at magnitudes of 0.04 and 0.06 ms^{-2} r.m.s. for frequencies from 22.5 Hz to 63 Hz and at 0.04 ms^{-2} r.m.s. for 11.3 Hz and 16 Hz motion). The larger slopes at high frequencies were reduced by the removal of imperceptible stimuli. For example, the slope at 31.5 Hz was reduced from 1.76 to 1.46 and at 44.5 Hz the slope was reduced from 1.57 to 1.54. However, the regression coefficients at high frequencies remained larger than at low frequencies. Thus, the imperceptibility of some stimuli at high frequencies may have contributed to the increase of the regression coefficient with frequency, but it does not provide a full explanation of the effect.

Figures 6.3 and 6.4 show the frequency weightings for z–axis and y–axis motion. The shape of the frequency weighting for vertical motion was similar at each magnitude. However, for horizontal motion, the slope of the frequency weighting increased negatively as the magnitude decreased. This effect arose from the increase in the regression coefficient relating subjective and objective magnitudes with increasing frequency. At high frequencies, large regression coefficients resulted in a greater distance between the frequency weightings corresponding to the six magnitudes. Figure 6.4 suggests a slight rise in the weightings for horizontal vibration at 63 Hz relative to 50 Hz. It may be appropriate to treat this trend with some caution as a small number of stimuli at this frequency were imperceptible to some subjects and there was a significant amount of cross-axis coupling in the vertical axis of the vibration (see Section 3.3.2.2). The average weightings for horizontal motion shown in Figures 6.5 and 6.7 are therefore connected with a dotted line above 50 Hz.

Figures 6.6 and 6.7 show the mean frequency weightings averaged over the six magnitudes for z-axis and y-axis motion compared with W_b and W_d frequency weightings defined in the British Standard 6841 (1987). The W_g frequency weighting defined in BS 6841 (1987) corresponds to an asymptotic approximation to the z-axis frequency weighting advocated in ISO 2631 (1978). Figure 6.6 indicates that the W_g frequency weighting for z-axis motion underestimates the importance of high frequencies. At frequencies below about 30 Hz, the results compare well with weighting W_b advocated in the British Standard for assessing subjective response to vertical vibration. Figure 6.7 suggests that the results for y-axis motion are in good agreement with W_d over the whole frequency range considered. This weighting is advocated for assessing horizontal vibration in both ISO 2631 (1978) and BS 6841 (1987).

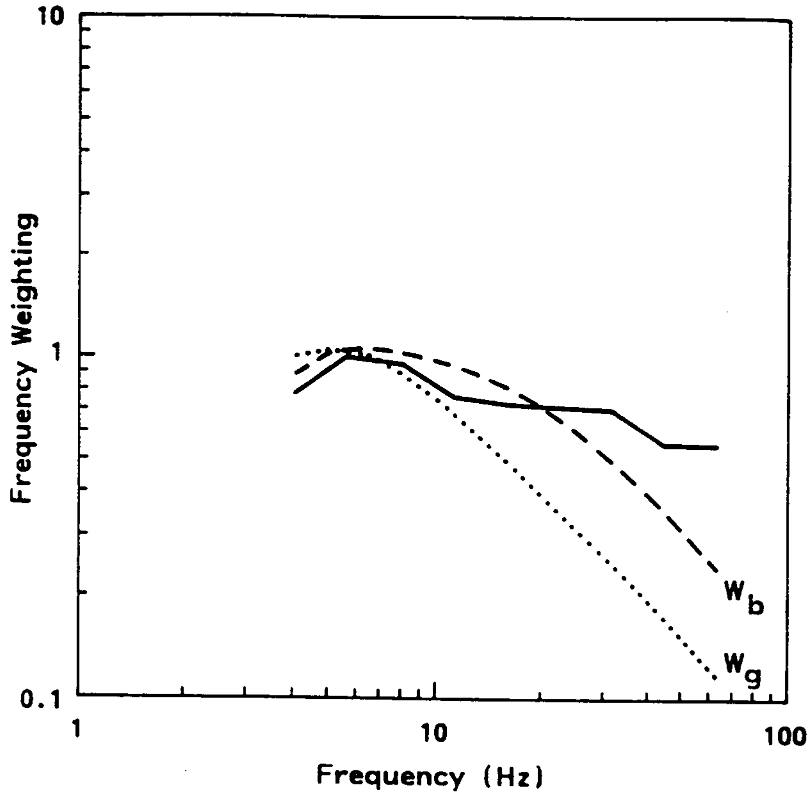

Figure 6.6 Comparison of vertical (z–axis) frequency weightings with W_b and W_g.

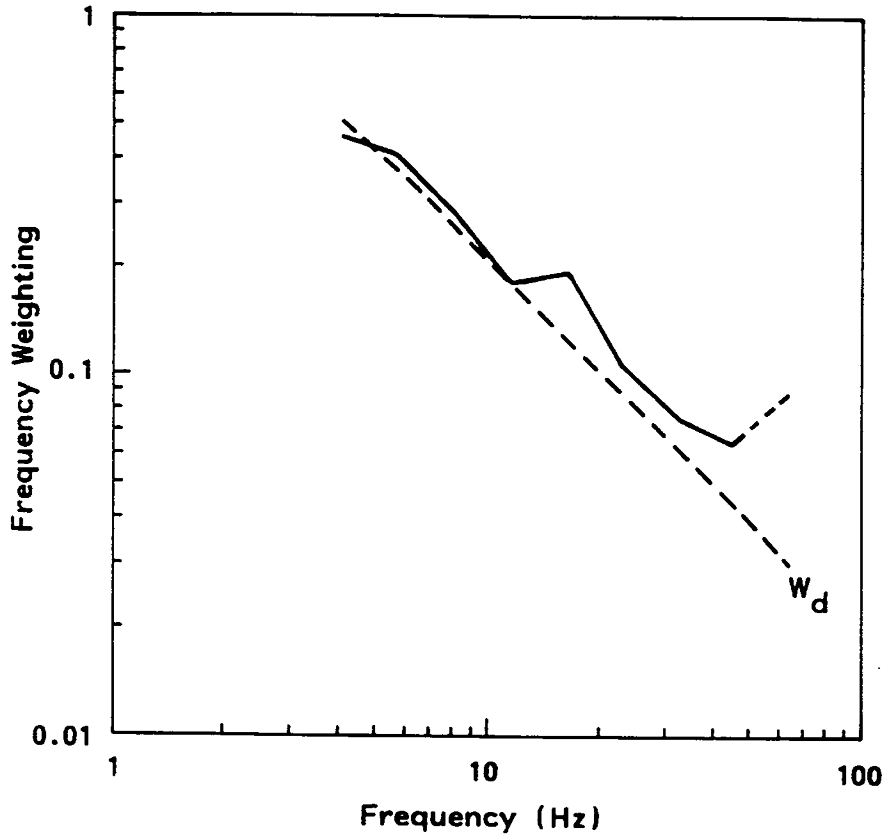

Figure 6.7 Comparison of horizontal (y–axis) frequency weightings with W_d. Weightings above 50 Hz are tentative.

The W_b and W_d frequency weightings defined in the British Standard 6841 (1987) were influenced by experimental determination of equivalent comfort contours for vertical and lateral vibration conducted by Griffin, Parsons and Whitham (1982) over the frequency range 1 to 100 Hz and by Corbridge and Griffin (1986) over the range 0.5 to 5 Hz. In Figures 6.8 and 6.9, the vertical and horizontal comfort contours obtained in these two studies are compared with annoyance contours from the present study. Previous contours were obtained by the method of constant stimuli and were subjectively equivalent to 0.8 ms^{-2} r.m.s. 10 Hz vertical vibration (Griffin, Parsons and Whitham, 1982) and 0.75 ms^{-2} r.m.s. 2 Hz vertical or horizontal vibration (Corbridge and Griffin, 1986). The curves determined by Corbridge and Griffin have been normalised with respect to those produced by Griffin et al at a frequency of 5 Hz. The annoyance contours presented in Figures 6.8 and 6.9 for the results of the present study correspond to three magnitude estimates: 50, 100 and 200, where 100 is subjectively equivalent to the sound reference stimulus. Even though the present study involved motion at much lower magnitudes the results have a similar frequency dependence to those of the previous studies but suggest slightly greater relative sensitivity at high frequencies.

The equivalence between z-axis and y-axis motion, shown in Figure 6.5 indicates that at all frequencies above about 5 Hz, a given magnitude of z-axis motion is subjectively greater than the same magnitude of y-axis motion. The horizontal frequency weightings depend on vibration magnitude but averaging over the six magnitudes of vibration indicates subjective equivalence between the two axes of motion is at 5 Hz. This is in approximate agreement with the International Standard ISO 2631 and the British Standard BS 6841 which both propose that equivalence occurs at 3.15 Hz.

The exponent in the psychophysical power law relating subjective and objective magnitudes appears to depend on some combination of vibration magnitude, frequency and direction.

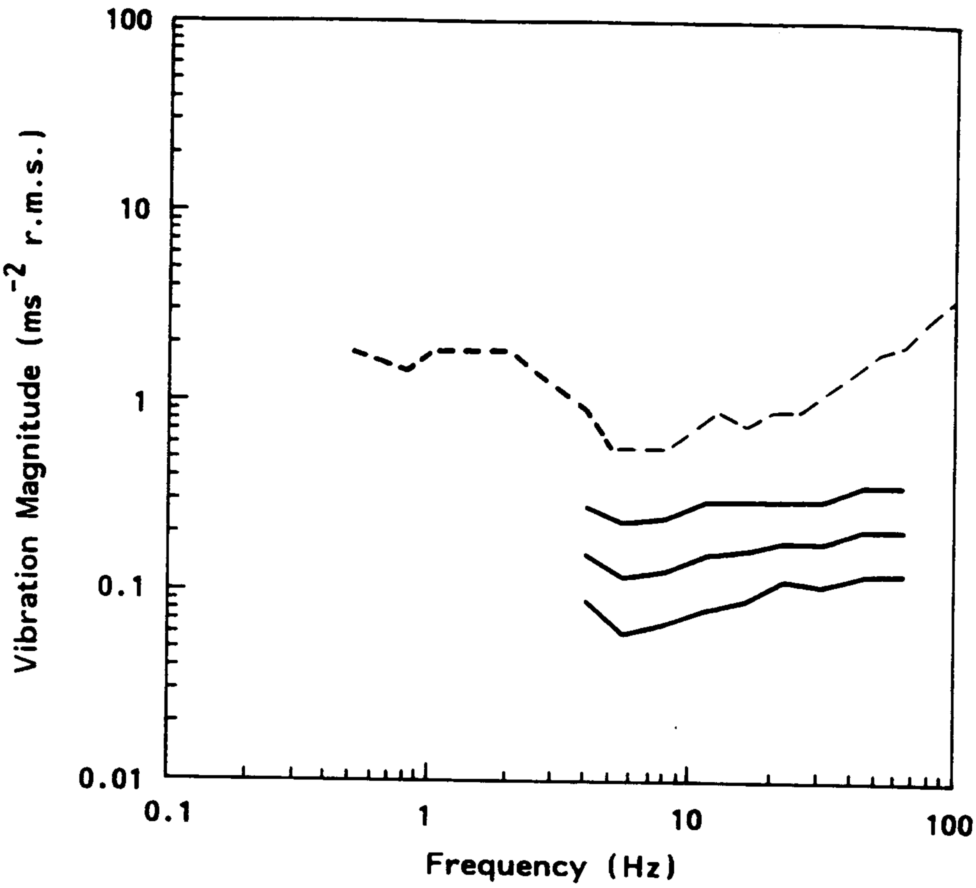

Figure 6.8 Comparison of vertical equal annoyance contours obtained in Experiment 5 for magnitude estimates of 50, 100 and 200 (——) with equivalent comfort contours for vertical motion reported by Corbridge and Griffin (1986) (----) and Griffin et al (1982) (----).

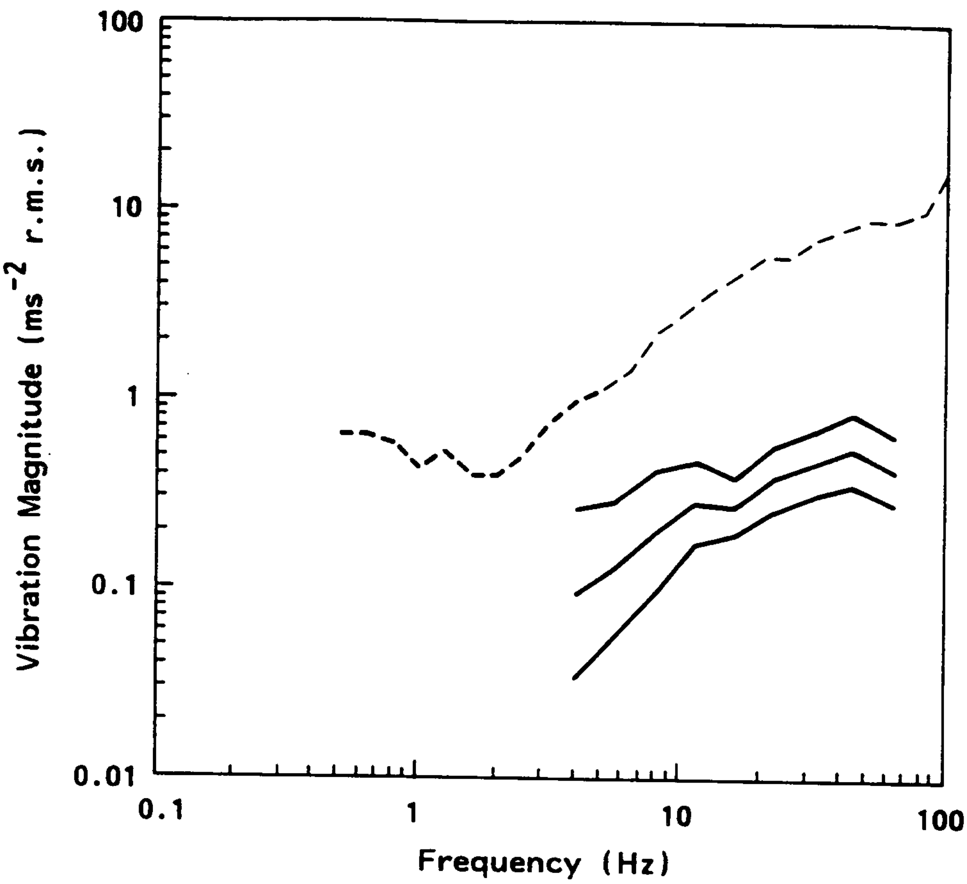

Figure 6.9 Comparison of horizontal equal annoyance contours obtained in Experiment 5 for magnitude estimates of 50, 100 and 200 (——) with equivalent comfort contours for horizontal motion reported by Corbridge and Griffin (1986) (——) and Griffin et al (1982) (----).

6.6 CONCLUSIONS

The exponent in the power function relating annoyance and objective magnitude was not frequency dependent for vertical motion but for horizontal motion the exponent increased with increasing frequency. This effect may have been the result of either a dependence on frequency or a dependence on magnitude.

Frequency weightings were determined to describe the effect of frequency of whole-body vibration at magnitudes which might occur in buildings during the passage of nearby trains. The results indicate that the weightings in British Standard 6841 (1987) provide a reasonable approximation of the frequency dependence of subjective response to whole-body vibration at low magnitudes. There is some evidence that the weightings may slightly underestimate the effect of high frequency vertical motion.

CHAPTER 7

PREDICTION OF THE ANNOYANCE FROM COMPLEX CONDITIONS OF SIMULTANEOUS NOISE AND VIBRATION FROM RAILWAYS

7.1 INTRODUCTION

The nature of vibration produced in buildings during the passage of nearby trains is complex. The intermittent events characterising railway-induced building vibration involve various directions, magnitudes, frequencies and durations of motion. The vibration usually occurs simultaneously with railway noise. A method of evaluating railway-induced building vibration, to provide a single measure indicating the relative annoyance caused by the stimuli, must allow for the influence of these variable characteristics. Experiments 1 to 5 were conducted to investigate separately the effect on annoyance of the variables characterising building vibration. This chapter describes Experiment 6 in which the findings of Experiments 1 to 5, concerning the influence of duration, magnitude and frequency of vibration and the effect of simultaneous noise and vibration, were combined to predict the relative annoyance produced by complex conditions of railway-induced building vibration and railway noise. The findings of Experiments 1 to 5 which were combined in Experiment 6 may be summarised: The results of Experiments 1 and 2 provided information on the effect of magnitude and duration in the form of a trade-off, $N \alpha V^{-4}$, between the number of passing trains, N, and the magnitude of the vibration, V. The influence of simultaneous noise and vibration was investigated in Experiments 3 and 4. The relative importance of noise and vibration and the interaction between responses to the two stimuli were determined. The fifth experiment was conducted to determine the influence of vibration frequency, vibration magnitude and vibration direction. Frequency weightings determined for vertical and lateral motion at low magnitudes were found to approximate the W_b and W_d frequency weightings defined in BS 6841 (1987).

Experiment 6 employed the method of magnitude estimation to determine the relative annoyance from different levels of simulated railway noise combined with different magnitudes of vertical vibration recorded in houses during the passage of six trains. The relative annoyance was predicted from a method which combined the findings of the previous experiments.

7.2 APPARATUS

The experiment took place in a representation of a small sitting-room. The subjects sat in a comfortable upright posture on a rigid wooden seat attached to an aluminium plate, which was secured to the vibrator table. The seat was slightly contoured to reduce the pressure on the ischial tuberosities. The seat was driven by a Derritron VP30 electromagnetic vibrator, powered by a 300 watt amplifier and was constrained to move in the vertical (z-) axis only. The feet and thighs of each subject were positioned horizontally and the lower legs vertically by means of an adjustable stationary footrest. A stationary wooden backrest was slightly contoured for comfort.

The acceleration time histories of the vibration stimuli were frequency weighted to compensate for the frequency response of the vibrator-subject combination (see Section 3.2.3). The vibration received by the subjects was measured by an accelerometer positioned under the centre of the seat. Computer generated vibration stimuli were used as the input to the vibrator amplifier via a 10 bit digital-to-analogue converter and an eight pole Butterworth low-pass filter at 100 Hz (48 dB per octave roll off). The digital-to-analogue and analogue-to-digital sampling rate was 501.7 samples per second.

A Bruel and Kjaer noise generator was used to produce the sound stimuli. The noise was presented to the subjects (via a Barr and Stroud EFS-20 filter set and an amplifier system) by two 100 watt Tannoy Mercury loudspeakers which were situated behind a curtain in front of the subject.

Section 3.2 provides full details of the apparatus and generation of the vibration and noise stimuli.

7.3 EXPERIMENTAL METHOD

7.3.1 Stimuli

The experiment involved exposure to reproductions of vertical vibration recorded in houses during the passage of six nearby trains. The vibration stimuli were presented simultaneously with simulated railway noise and were selected to consist of different frequencies and durations of vertical vibration. The acceleration power spectral densities for the vibration stimuli of the six trains are shown in Figure 7.1. The sound stimuli consisted of broad band random noise with frequencies in the range 20 Hz to 3 kHz and were generated by passing pink noise through a band-pass filter (roll off 48 dB/octave). (Pink noise is a continuous spectrum random noise that has a spectrum which declines as a function of frequency at the rate of 3 dB per octave.) The sound stimuli were then shaped so that the noise level varied with time in a similar manner to the simultaneous vibration stimuli. The running root-mean-square acceleration time histories of the six vibration stimuli were obtained using a two-second averaging time and a one-sample increment (0.002 s). Pink noise was multiplied by the resulting r.m.s. time histories to produce the shaped noise stimuli. The running root-mean-square acceleration time histories of the vibration stimuli which were multiplied by the pink noise to shape the noise stimuli are shown in Figure 7.2. The figure shows the r.m.s. acceleration of each train at the maximum vibration magnitude presented. The acceleration is proportional to the pressure of the corresponding noise stimuli. The background acoustic noise level at the position of the subject's head was 42 dB(A) and was primarily due to the cooling system of the vibrator.

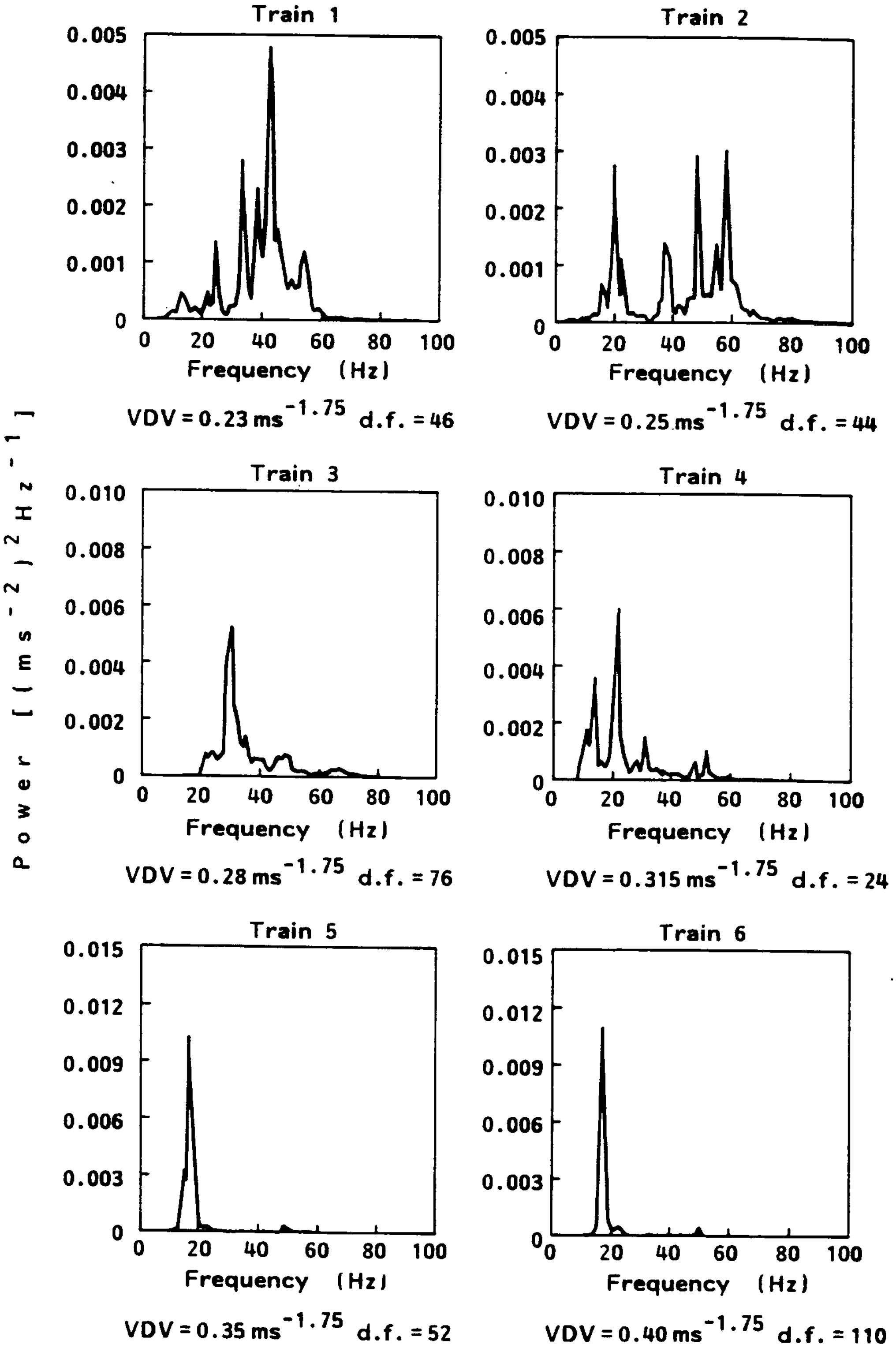

Figure 7.1 Acceleration power spectral densities of vibration stimuli for maximum magnitude of each train. Resolution 1 Hz.

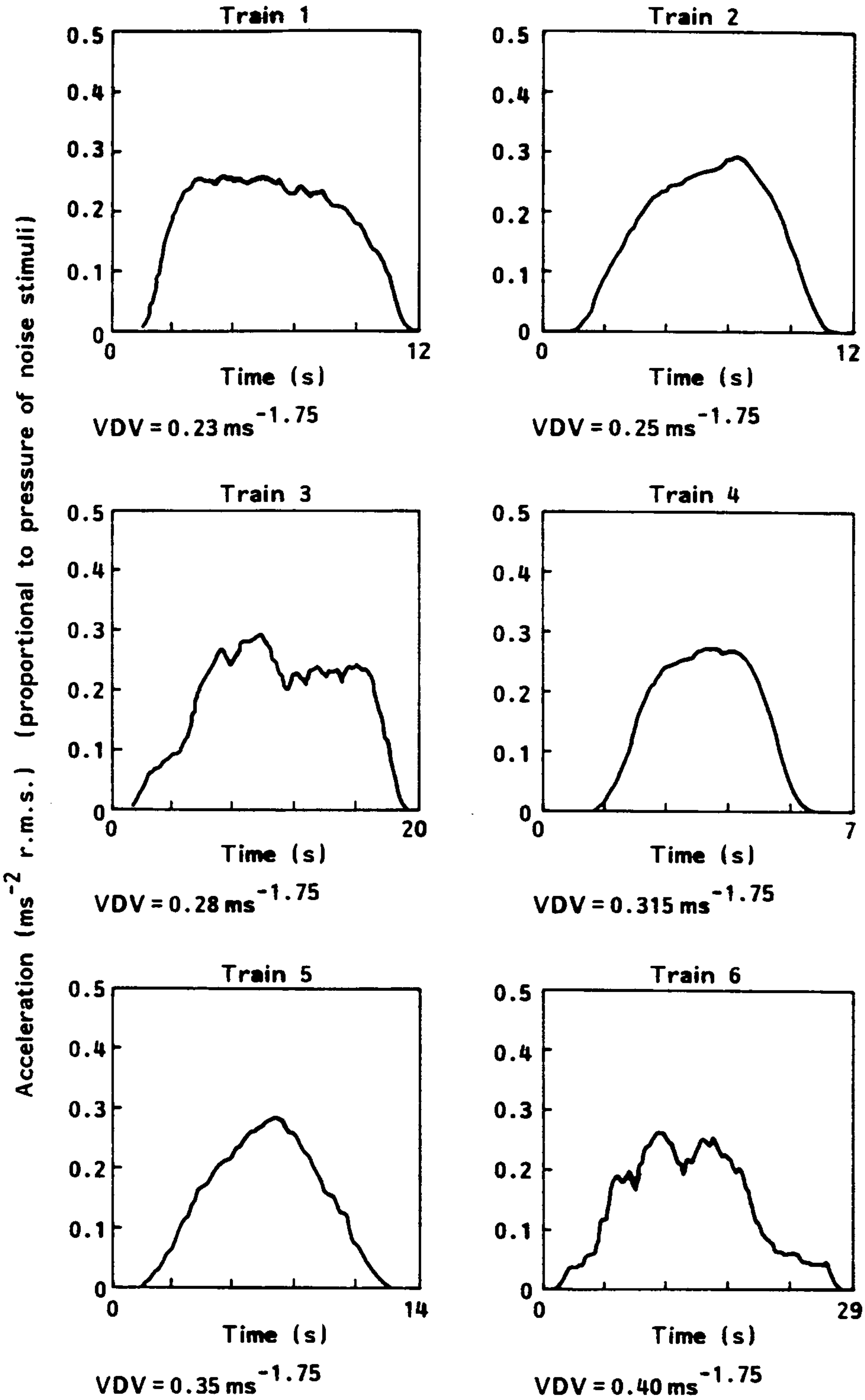

Figure 7.2 Running root-mean-square vertical acceleration time-histories employed to shape noise stimuli. Maximum vibration magnitude of each train.

The passage of each train was presented to the subjects at three levels of noise combined with three magnitudes of vibration. All 15 paired combinations of noise and vibration were presented, including single stimulus conditions. Table 7.1 shows the exposure duration, vibration frequency range, vibration dose values and sound exposure levels of the stimuli. (Appendix 2 provides a definition of the sound exposure level.) The vibration dose values were selected so that there was an increase by a factor of 1.122 (1 dB) between successive magnitudes of all the trains. The three sound exposure levels of each train were subjectively equivalent to the three vibration dose values, according to the relation describing the subjective equality between noise and vibration obtained in Experiment 3 ($L_{AE} = 29.3 \log_{10} VDV + 89.2$). (Section 5.4 provides details of Experiment 3.)

Train Number	Duration (seconds)	Vibration Frequency (Hz)	VDV ($ms^{-1.75}$)	L_{AE} (dB(A))
1	12	30-50	0.056 0.113 0.230	52.5 61.5 70.5
2	12	20-60	0.063 0.127 0.250	54.0 62.9 71.5
3	20	30	0.070 0.140 0.280	55.4 64.2 73.0
4	7	10-25	0.080 0.160 0.315	57.1 65.9 74.5
5	14	18	0.090 0.180 0.350	58.5 67.4 75.8
6	29	18	0.100 0.200 0.400	60.0 68.7 77.5

Table 7.1 Exposure duration, vibration frequency, vibration dose values (VDV) and sound exposure levels (L_{AE}) of the stimuli.

7.3.2 Procedure

Ten men and ten women aged between 21 and 61 acted as paid subjects in the experiment. All subjects were shown a list of medical conditions which would have rendered them unfit for participation in the experiment (BSI, 1973). The subjects were instructed to adopt a comfortable upright seated posture during the experiment, which lasted approximately one hour. The method of magnitude estimation was employed to indicate the relative disturbance produced by each combination of noise and vibration.

Before the experiment, each subject was given practice at using the method of magnitude estimation by assigning numbers to lines according to their length (Appendix 7.1). The subjects were then presented with the reference stimulus followed by four practice stimuli. They were then given an opportunity to ask questions before starting the experiment.

Ninety test stimuli (15 combinations of noise and vibration for each of the six trains) were presented in a different random order to each subject. The reference stimulus consisted of combined noise and vibration corresponding to train Number 3 at the middle magnitudes of noise and vibration: VDV = 0.140 $ms^{-1.75}$ and L_{AE} = 64.2 dB(A). The reference stimulus was presented before every group of four test stimuli and the annoyance it caused was indicated as corresponding to a value of 100. The subjects assigned a number to each test stimulus to indicate the annoyance it would cause, as a multiple of the reference stimulus, if it were to occur in a house. The instructions are shown in Appendix 7.2.

A digital computer was employed to generate the vibration stimuli, to shape the noise stimuli, to determine the overall r.m.s. acceleration magnitude of each vibration stimulus and to store each magnitude estimate. The high magnitudes of the vibration stimuli differed from the expected magnitudes due to the non-linear response of the vibrator. Therefore, analysis of the results involved the measured r.m.s. acceleration magnitude of all stimuli presented to all subjects. The vibration dose value and the overall r.m.s. acceleration of each stimulus presented to the final subject was determined. The mean vibration dose values were determined by making the assumption that the ratio between the vibration dose value and the r.m.s. acceleration for each stimulus presented to the final subject was the same as the ratio between the mean vibration dose value and the mean r.m.s. acceleration for each stimulus averaging over all subjects.

7.4 RESULTS AND DISCUSSION

Linear regression analysis was conducted on the magnitude estimates for the conditions when subjects were presented with either noise alone or vibration alone. This led to the evolution of psychophysical power functions for noise and for vibration. Figure 7.3 shows the logarithm of the median magnitude estimate, $\log_{10} \psi_s$, as a function of the sound exposure level, $\log_{10} \varphi_s$, together with the regression line. The regression equation was given by:

$$\log_{10} \psi_s = 0.036 \log_{10} \varphi_s - 0.512$$

where $$\log_{10} \varphi_s = L_{AE} \text{ (dB(A))}$$

from which $$\psi_s = 0.307 \varphi_s^{0.036}$$

The correlation coefficient ($r = 0.917$) was highly significant ($p < 0.005$). The value of the exponent in the psychophysical power function, 0.036, is similar to the value of 0.039 determined in Experiment 4 (see Section 5.5). It is also in agreement with the relation determined by Stevens (1986) to equate loudness, L, and sound pressure level, SPL, which indicates a growth function of 0.033. The relation is given by:

$$\log_{10} L = 0.033 \text{ SPL} + k$$

where k is a constant. (Appendix 5, Section A5.1.5 provides a discussion of studies of the growth function relating loudness and noise intensity.)

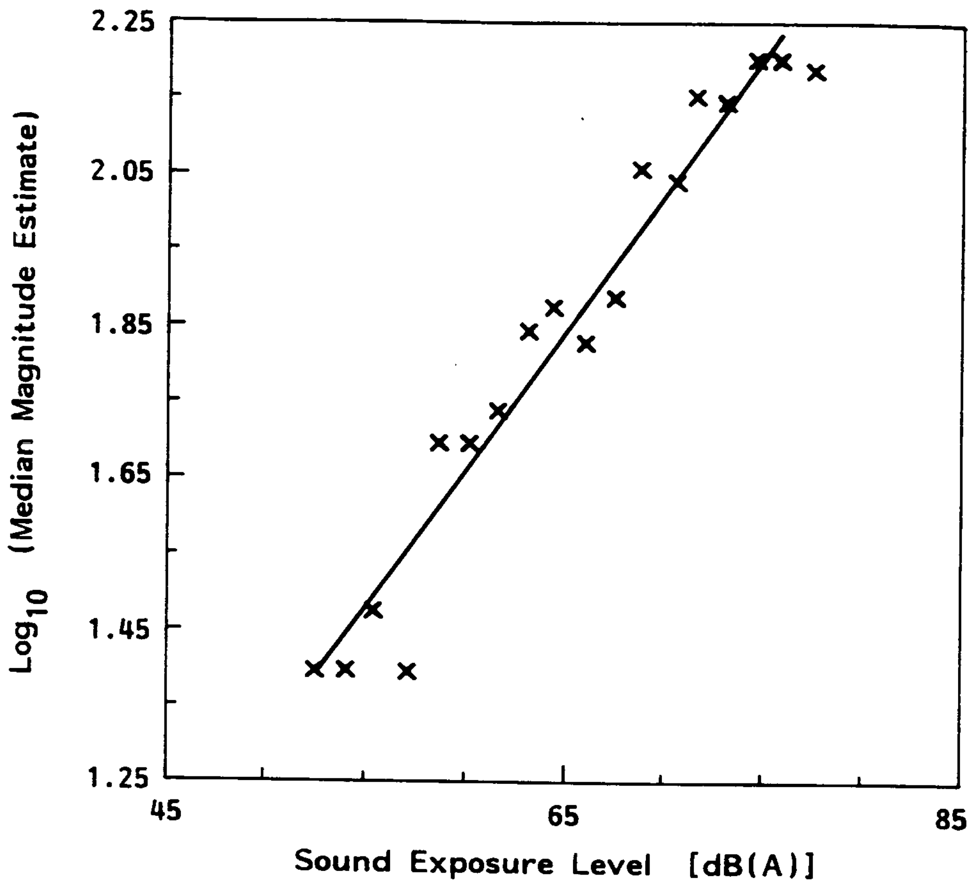

Figure 7.3 Magnitude estimate as a function of sound exposure level.

Figure 7.4 shows the regression line relating the logarithm of the magnitude estimate, $\log_{10} \psi_v$, and the logarithm of the vibration dose value, $\log_{10} \varphi_v$. The regression equation was given by:

$$\log_{10} \psi_V = 1.18 \log_{10} \varphi_V + 2.57$$

where φ_V = VDV ($ms^{-1.75}$)

from which $\psi = 371\ \varphi_V^{1.18}$

The correlation coefficient ($r = 0.973$) was highly significant ($p < 0.005$). The value of the vibration exponent of 1.18 is similar to the value of 1.04 determined in Experiment 4 (see Section 5.5) and compares well with the mean values determined by magnitude estimation of 1.13 in a study by Fothergill and Griffin (1977) and of 0.96 and 1.20 in a study by Hiramatsu and Griffin (1984).

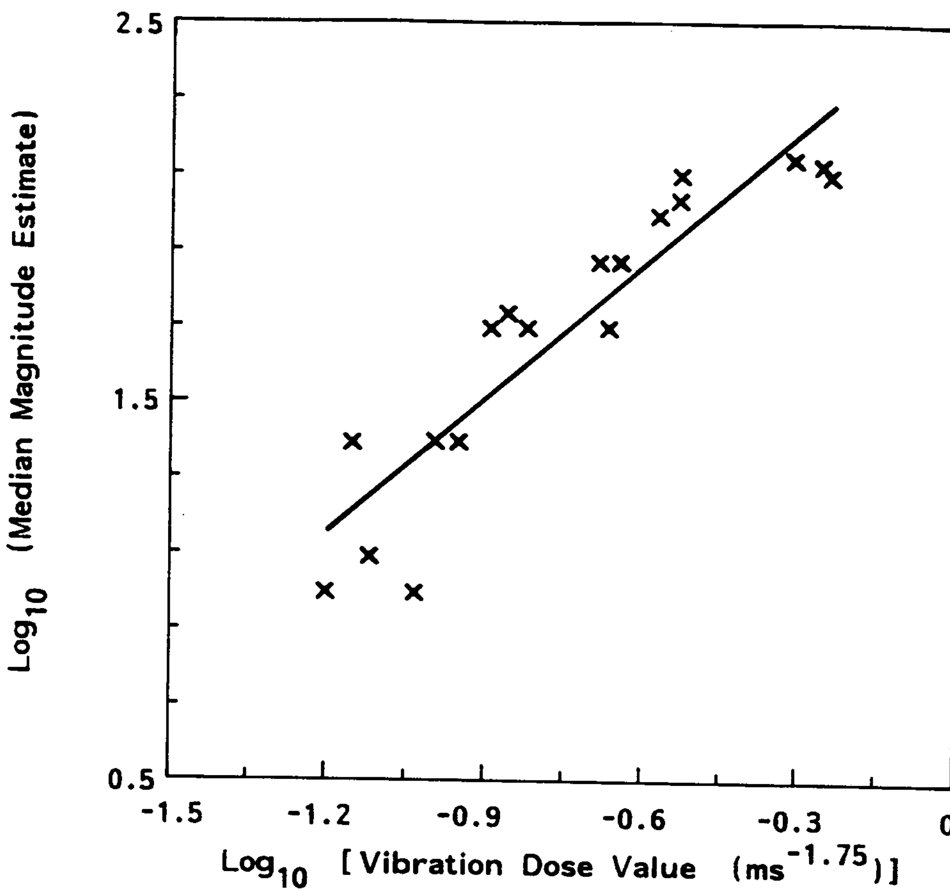

Figure 7.4 Magnitude estimate as a function of vibration dose value.

A means of predicting the total annoyance produced by combined noise and vibration from the individual effects of the two stimuli was determined using the same method employed in Experiment 4 (see Section 5.5.4). The assumption was made that the overall annoyance, ψ, may be approximated by a summation of the individual effects of the two stimuli and thus may be described by a relation of the form:

$$\psi = a + b\varphi_V^{n_V} + c\varphi_S^{n_S}$$

where n_s is the exponent in the psychophysical power function for noise,
n_v is the exponent in the psychophysical power function for vibration,
a, b and c are constants.

The values of the noise exponent, n_s, and the vibration exponent, n_v, determined from the single stimulus conditions, were used to evaluate the equation for the total annoyance by multiple regression analysis of the magnitude estimates, ψ, on two variables, $\varphi_s^{0.036}$ and $\varphi_v^{1.18}$. The resulting relation was given by:

$$\psi = 22.7 + 243\ \varphi_V^{1.18} + 0.265\ \varphi_S^{0.036} \qquad (7.1)$$

The correlation coefficient ($r = 0.958$) was highly significant ($p < 0.005$).

The magnitude estimates predicted from the relation for the combined effects of noise and vibration defined by Equation 7.1 are compared with the median magnitude estimates for the 90 stimuli presented to each subject in Figure 7.5. If the median and predicted magnitude estimates were identical, the data points would fall on the continuous line.

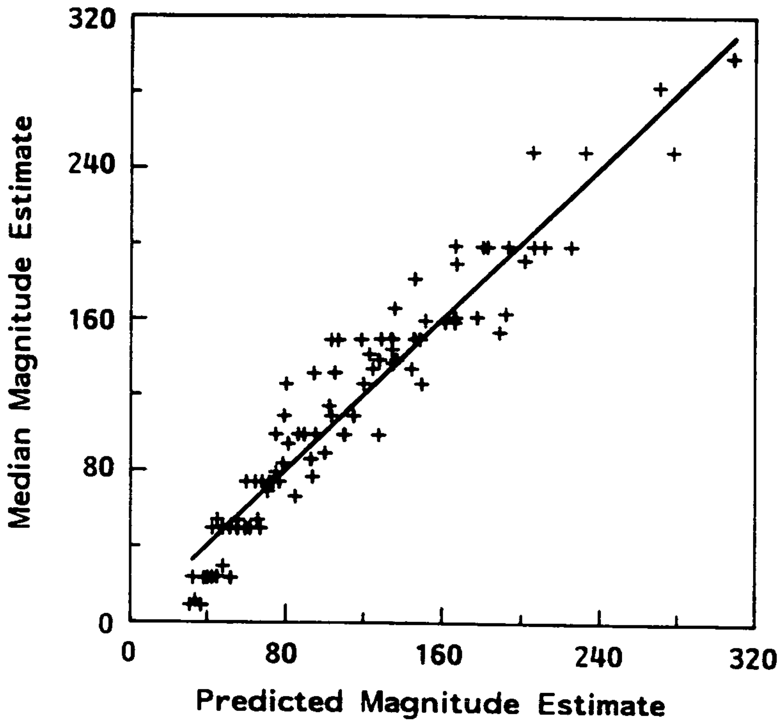

Figure 7.5 Comparison of median magnitude estimates with predicted magnitude estimates given by Equation 7.1 ($\psi = 22.7 + 243\varphi_V^{1.18} + 0.265\ \varphi_S^{0.036}$).

A relation between magnitude estimates and the vibration dose values alone was determined by linear regression analysis of the magnitude estimates of all combinations of noise and vibration on one variable, $\varphi_V^{1.18}$. The resulting relation was given by:

$$\psi = 82.2 + 240\ \varphi_V^{1.18} \qquad (7.2)$$

where $$\varphi_V = \text{VDV } (\text{ms}^{-1.75})$$

The correlation coefficient ($r = 0.573$) was significant ($p < 0.005$), however, it was significantly smaller than the correlation coefficient obtained from Equation 7.1. This indicates that a more accurate prediction of the annoyance may be obtained from a relation involving a summation of the effects of both stimuli (Equation 7.1) than from a relation involving the vibration dose value alone (Equation 7.2).

Similarly, a relation was determined between magnitude estimates and the sound exposure levels alone by linear regression analysis. The relation was given by:

$$\psi = 58.8 + 0.263\ \varphi_S{}^{0.036} \tag{7.3}$$

where

$$\log_{10} \varphi_S = L_{AE}\ (\text{dB(A)})$$

The correlation coefficient ($r = 0.762$) was significant ($p < 0.005$), however, it was significantly less than the correlation coefficient obtained from Equation 7.1 which involved the effects of noise and vibration. Figures 7.6 and 7.7 show the median magnitude estimates as a function of the magnitude estimates predicted from Equations 7.2 and 7.3 respectively.

Comparison of Figure 7.5 with Figures 7.6 and 7.7 illustrates the greater correlation between the magnitude estimates and the values predicted from a method involving the summation of the individual effects of noise and vibration, than from a method based on only one variable, either the vibration dose value or the sound exposure level.

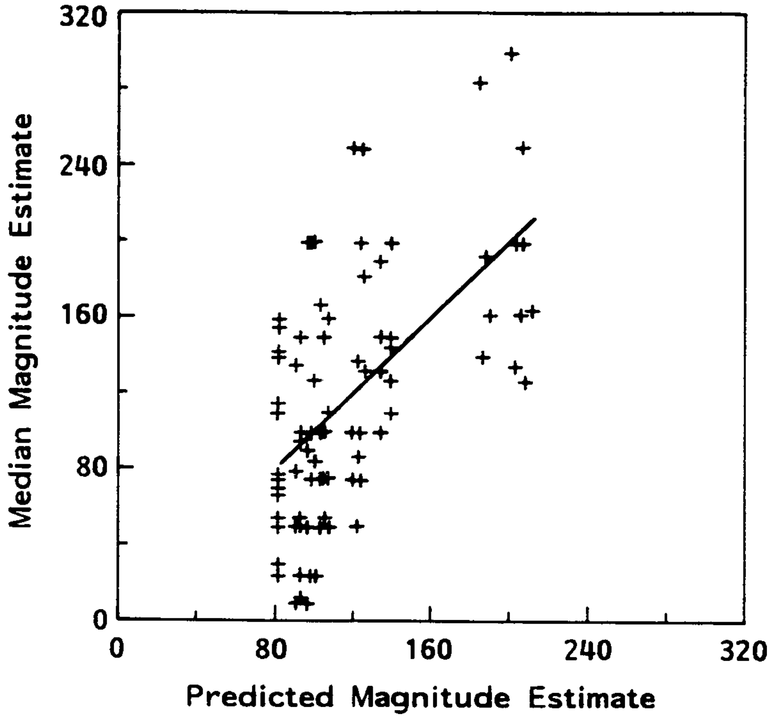

Figure 7.6 Comparison of median magnitude estimates with predicted magnitude estimates given by Equation 7.2 (ψ = 82.2 + 240 $\varphi_v^{1.18}$).

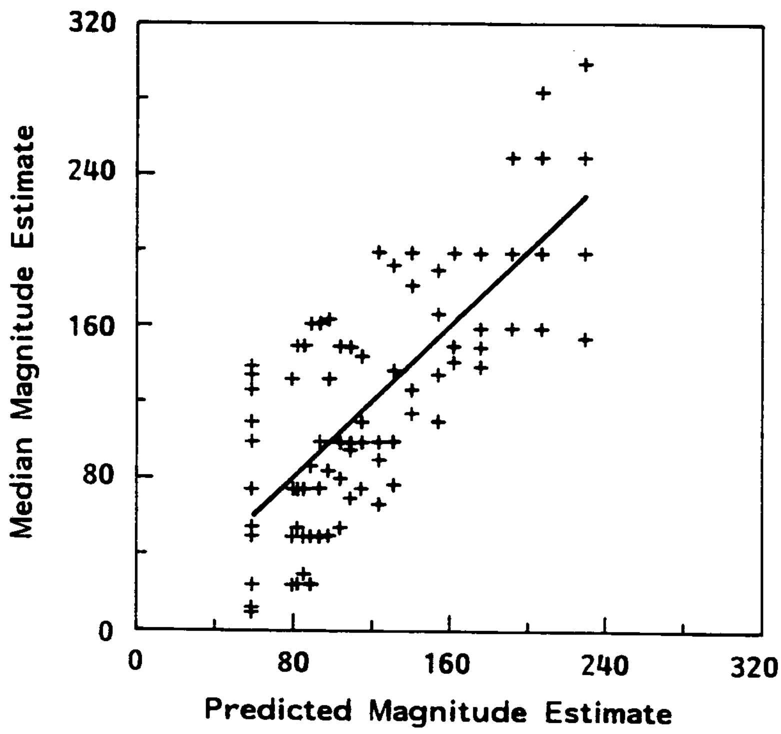

Figure 7.7 Comparison of median magnitude estimates with predicted magnitude estimates given by Equation 7.3 (ψ = 58.8 + 0.263 $\varphi_s^{0.036}$).

Linear regression analysis was conducted to obtain a relation between the magnitude estimate and the unweighted root-mean-square acceleration, a, of each stimulus. The relation was given by:

$$\psi = 76.1 + 417\ a \qquad (7.4)$$

The correlation coefficient ($r = 0.524$) was significant ($p < 0.005$). Figure 7.8 shows the magnitude estimates as a function of the magnitude estimates predicted from the root-mean-square acceleration (Equation 7.4). Linear regression involving the vibration dose value (Equation 7.2) resulted in a slightly greater correlation coefficient than the method involving the root-mean-square acceleration (Equation 7.4). However, the difference between the correlation coefficients of Equations 7.2 and 7.4 was not significant. This suggests that the unweighted root-mean-square acceleration may be an equally appropriate method of evaluating vibration as the vibration dose value. The vibration stimuli were selected to represent the range of durations and frequencies of vibration which may be generated in a house during the passage of a single train. The stimuli consisted of a fairly large range of frequencies (approximately 10 Hz to 60 Hz) and therefore, contrary to the findings, it was expected that the vibration dose value, which applied a frequency weighting, would have resulted in significantly better correlations with the annoyance than the unweighted root-mean-square acceleration method. The duration of the largest stimulus (Train 6) was about four times the duration of the shortest stimulus (Train 4). The vibration dose value assumes a time dependency based on a four fold increase in duration corresponding to an increase in annoyance of a factor of only 1.4. Therefore, it is not surprising that the differences in the durations of the vibration stimuli may not have been large enough to produce a significant effect on the annoyance. However, Experiments 1 and 2 which involved longer periods of time consisting of different numbers of events and therefore a greater range of vibration durations revealed limitations of the root-mean-square acceleration as an evaluation method.

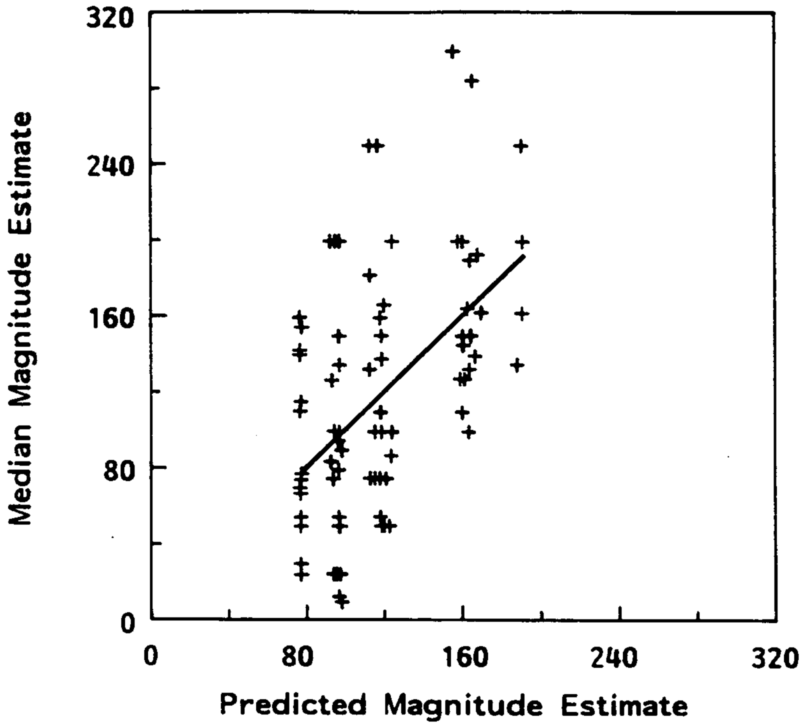

Figure 7.8 Comparison of median magnitude estimates with predicted magnitude estimates given by Equation 7.4 (ψ = 76.1 + 417 a).

Table 7.1 shows the levels of significance of the differences between the correlation coefficients of the four relations given by Equations 7.1 to 7.4 (Edwards, 1976). The table shows that the difference is highly significant ($p < 0.0001$) between the correlation coefficient of the Equation 7.1, which involves the effects of noise and vibration, and of each of the other three equations (7.1, 7.2 and 7.3) which involve the effects of only one stimulus. Equation 7.3, involving the effects of noise only, provided a significantly greater correlation coefficient than Equations 7.2 ($p = 0.01$) and 7.4 ($p < 0.005$) which involve the effects of vibration only. This implies that the responses were more influenced by the reaction to the noise. Therefore, there may have been a greater change in annoyance over the range of noise levels than over the range of vibration magnitudes.

Equation No.		7.1	7.2	7.3	7.4
	Correlation r	0.958	0.573	0.762	0.524
7.1	0.958		***	***	***
7.2	0.573			*	-
7.3	0.762				**
7.4	0.524				

*** $p < 0.0001$

** $p < 0.005$

* $p < 0.01$

– not significant

Table 7.1 Levels of significance of differences (p) between correlation coefficients of Equations 7.1 to 7.4.

The relation predicting the annoyance produced by simultaneous noise and vibration from the summation of the individual effects of the two stimuli (Equation 7.1) can be employed to determine a relation for the subjective equivalence of noise and vibration. The equivalence between the two stimuli was given by:

$$L_{AE} = 32.4 \log_{10} \mathrm{VDV} + 81.6 \qquad (7.5)$$

In Figure 7.9 the subjective equivalence curve corresponding to Equation 7.5 is compared with the equivalence curves determined in Experiment 3 and Experiment 4 (see Chapter 5). The equivalence curves are shown for the range of vibration magnitudes employed in the experiments. (The actual vibration magnitudes in Experiment 6 ranged from 0.06 $ms^{-1.75}$ to 0.60 $ms^{-1.75}$.) The relations for the curves of Experiments 3 and 4 were given by:

$$L_{AE} = 29.3 \log_{10} \mathrm{VDV} + 89.2 \qquad \text{(Experiment 3)}$$

and

$$L_{AE} = 26.7 \log_{10} \mathrm{VDV} + 81.7 \qquad \text{(Experiment 4)}$$

The gradient of the equivalence curve corresponds to the ratio of the exponents in the power functions (n_v/n_s). Since the value of n_v is usually unity and the values of n_s is approximately 0.033, the gradient of the equivalence line should be about 30. Equivalence curves from the results of the three experiments have gradients approximately equal to the expected value. The differences between the gradients of the three curves are relatively small.

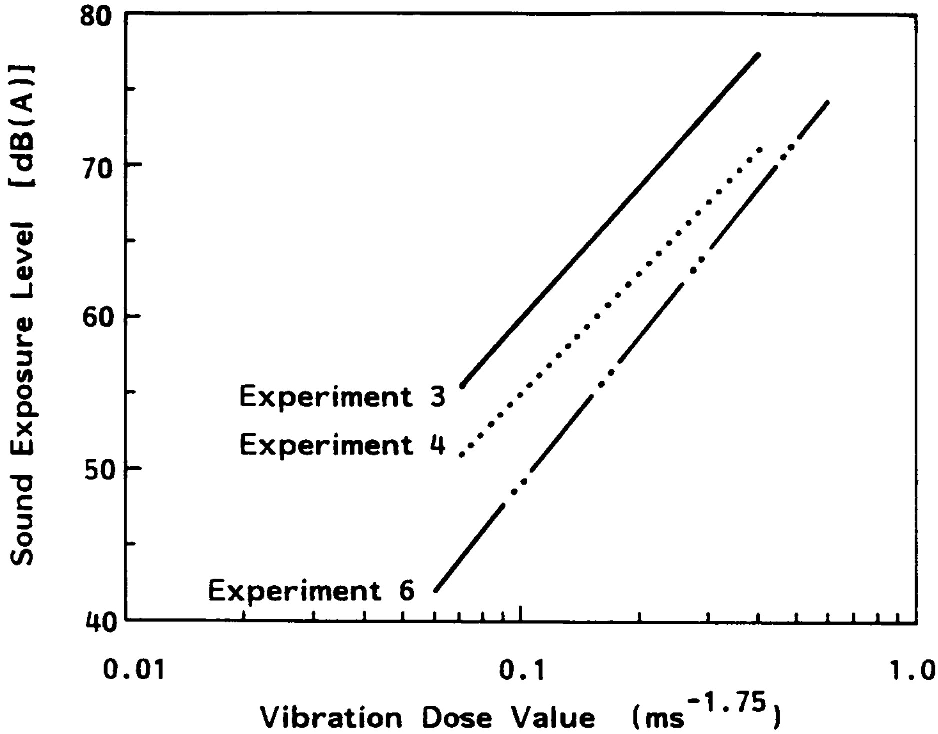

Figure 7.9 Comparison of equivalence curves from Experiments 3 and 4 with equivalence curve of Equation 7.5.

The subjective equivalence curve obtained from the results of Experiment 3 corresponds to noise levels equivalent to vibration which are about 6 dB greater than the equivalence curve from Experiment 4 and about 10 dB greater than the curve from Experiment 6. These differences may be partly a result of different stimuli ranges. The noise levels employed in Experiment 3 (L_{AE} = 59 to 84 dB(A)) were 5 dB greater than for Experiment 4 (L_{AE} = 54 to 79 dB(A)) and 6.5 dB greater than for Experiment 6 (L_{AE} = 52.5 to 77.5 dB(A)), whereas the ranges of vibration magnitudes were similar. If the subjects had a tendency to normalise their responses, the curve for Experiment 4 would be 5 dB lower and the line from Experiment 6 would be 6.5 dB lower than the line from Experiment 3. An effect of this type was exposed by Garner (1959) with the method of ratio estimation. Garner believed that differences in the results of experiments on judgements of loudness may have been partly attributable to context effects.

Garner claimed to have trained different groups of subjects to state that the half-loudness of a 90 dB tone was either 60, 70 or 80 dB depending on the range of intensities available to each group as a choice of half-loudness.

It is concluded that differences between the equivalence curves from Experiments 3, 4 and 6 might be attributable to differences in the ranges of noise levels and to different experimental techniques. It may be considered that the results of Experiment 3 were less likely to have been biased by the regression effect than the results of Experiments 4 and 6. The task of subjects during Experiment 3 was to indicate whether they would prefer the noise or the vibration to be reduced. This task was easier than the method of magnitude estimation employed in Experiments 4 and 6 and therefore may have provided more accurate results. It seems reasonable to assume that results obtained from a task involving the assignment of an infinite choice of numbers is more likely to be subject to biases than a task involving a choice of the reduction of one of two stimuli. Therefore, it may be appropriate to propose tentatively that the subjective equivalence of noise and vibration can be described by the relation determined in Experiment 3 which is given by:

$$L_{AE} = 29.3 \log_{10} VDV + 89.2$$

In Figure 7.10 the subjective equivalence curves determined from the results of Experiments 3, 4 and 6 are compared with the equivalence curves from studies by Fleming and Griffin (1975), Hempstock and Saunders (1973) and Kjellberg et al (1985). (These studies are reviewed in Section 2.6.) The gradients of the six curves, which correspond to the ratio of the exponents in the power functions of the two stimuli (n_v/n_s), are all in approximate agreement with the expected value of 30. The equivalent levels of vibration and noise determined from the results of the studies by Kjellberg et al and Hempstock and Saunders, in which subjects adjusted the magnitude of one stimulus (noise or vibration) to match the other stimulus, were similar to the equivalent levels determined from Experiments 4 and 6 which employed the method of magnitude estimation. Noise levels equivalent to higher vibration magnitudes were obtained from the results of Experiment 3. Fleming and Griffin employed the same experimental technique as Experiment 3 and similar results were obtained.

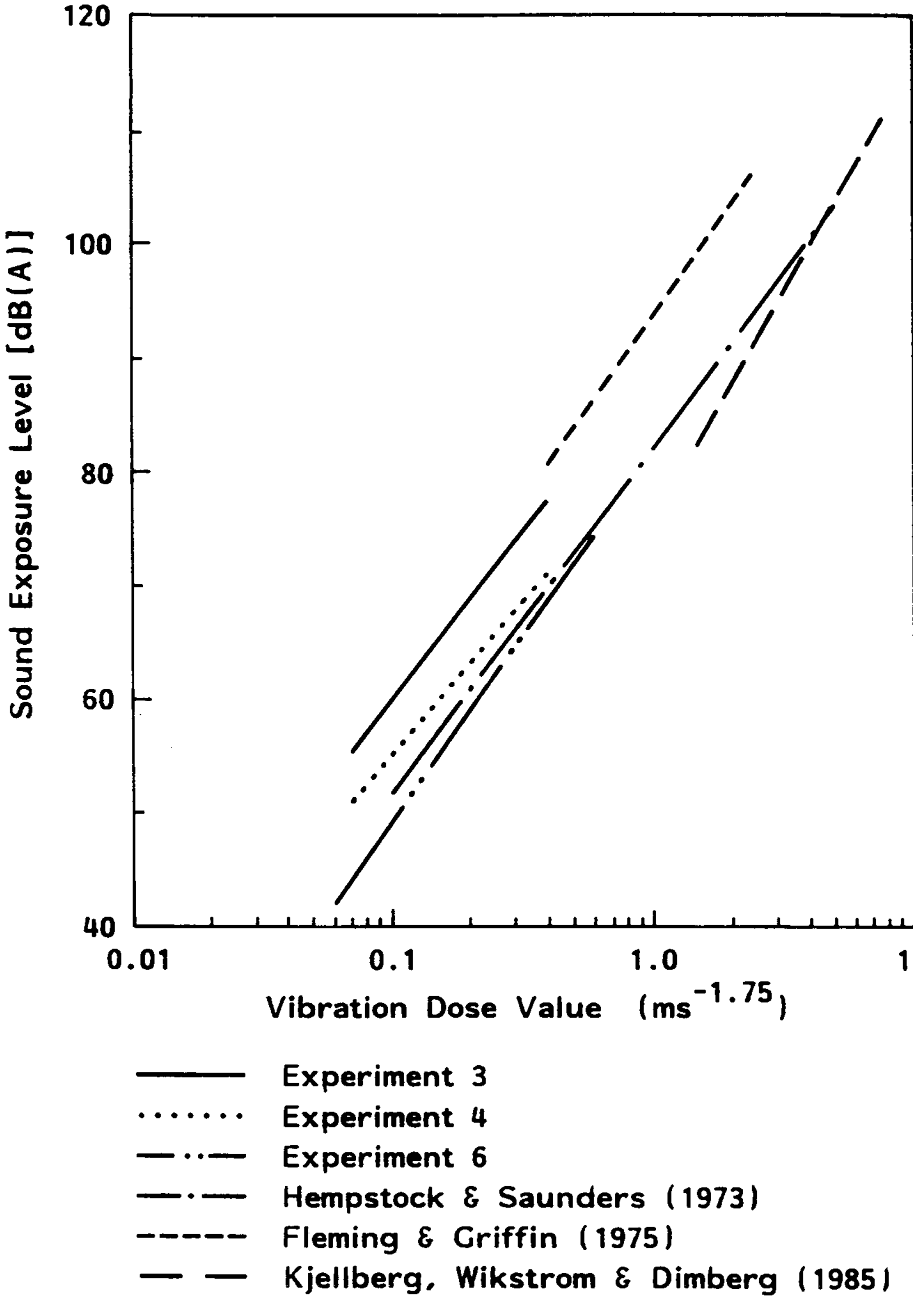

Figure 7.10 Comparison of subjective equivalence curve from Experiments 3, 4 and 6 and from previous studies.

The relation devised in this experiment (Equation 7.1) to describe the annoyance produced by simultaneous noise and vibration consists of three terms: the contribution of noise to the annoyance (0.265 $\varphi_s^{0.036}$), the contribution of vibration to the annoyance (243 $\varphi_v^{1.18}$) and a constant (22.7). The latter may be considered as the contribution of the background noise to the overall annoyance. From Equation 7.1 it may be calculated that at the lowest levels of noise and vibration presented in Experiment 6, the constant term accounted for approximately 40% of the total annoyance. At the highest levels of noise and vibration, the constant accounted for about 7% of the annoyance. Experiments 4 and 6 involved the presentation of the same sound exposure levels and vibration dose values for the reference stimuli which were both assigned the value of 100. Therefore, the relation determined in Experiment 4 for the response to noise and vibration (ψ = 15.9 + 260 $\varphi_v^{1.04}$ + 0.167 $\varphi_s^{0.039}$) may be expected to indicate the same value for the constant, since the two experiments were conducted in the same ambient conditions. A value of 15.9 (Experiment 4) may be considered similar to a value of 22.7 (Experiment 6) when the range of magnitude estimates assigned is considered.

7.5 CONCLUSIONS

The results of Experiment 6 have shown that a method of evaluating simultaneous noise and vibration has been devised which provides an approximation of the total relative annoyance by allowing for the influence of magnitude, frequency and duration of the two stimuli. It has been shown that a method based on the summation of the individual effects of the two stimuli provides a more accurate prediction of the total disturbance than a method involving either noise or vibration alone.

The relation determined in Experiment 6 predicting the relative annoyance produced by simultaneous noise and vibration was employed to determine the subjective equivalence of noise and vibration. The equivalence curve corresponded to noise levels equivalent to vibration which were about 4 dB less than the equivalence curve of Experiment 4 and 10 dB less than the equivalence curve of Experiment 3. Differences between the equivalence curves may be attributed to the regression effect and to different experimental techniques.

The relation for the effects of combined noise and vibration (Equation 7.1) has two practical applications. It may be employed to determine the relative importance of railway noise and railway-induced building vibration and it provides a means of comparing the annoyance from different combinations of railway noise and vibration. The method was derived from stimuli less than 29 seconds in duration. It may not be appropriate to apply it to exposure durations much greater than several minutes.

CHAPTER 8

SUMMARY OF CONCLUSIONS, APPLICATION OF THE RESULTS AND RECOMMENDATIONS OF FUTURE RESEARCH

8.1 INTRODUCTION

This chapter provides a summary of the objectives, conclusions and relevance of the findings of each experiment. The first four sections (Sections 8.2.1 to 8.2.4) relate to the four experimental chapters (Chapters 4 to 7). Each experiment provided information not previously available on the effect of a different characteristic of railway-induced building vibration. All the investigations were essential for the evaluation of an exhaustive method of assessing combined railway vibration and noise which may be used to predict the annoyance caused. In the light of the results, procedures of assessment are recommended in the fifth section. A further section provides examples of the application of these procedures. Finally, areas of future research are suggested.

8.2 SUMMARY OF OBJECTIVES AND CONCLUSIONS

8.2.1 The Annoyance Produced by Intermittent Railway-Induced Building Vibration

Railway-induced building vibration occurs at magnitudes near the threshold of perception and consists of variable durations of intermittent events. A review of previous studies (see Section 2.2) showed that in order to establish a method for the assessment of vibration from railways, further investigations were required to determine the growth of subjective magnitude as a function of objective magnitude of vibration at magnitudes near the perception threshold. A method of assessing railway vibration must accumulate the motion over time in a manner which allows for the time dependency of reaction to whole-body vibration. Examination of previous experimental investigations of the effect of duration on the response to vibration (see Section 2.3) showed that there is much evidence to indicate that a time dependency defined by an exponent of 2 relating acceleration magnitude, a, and duration, t, ($a^2t = k$) overestimates the effect of duration on the response to vibration. Further investigations were necessary to establish the time dependency of intermittent vibration, such as produced by trains.

Two experiments (Experiments 1 and 2) were conducted to investigate the effect on annoyance of the number of trains and the magnitude of vibration (see Chapter 4). A further objective was to determine a trade-off between vibration duration and vibration magnitude. The annoyance from railway-induced building vibration was shown to increase with an increase in the magnitude of the vibration and with an increase in the number of trains. The trade-off between the vibration magnitude, V, and the number of trains (vibration duration), N, was determined as approximately $N \alpha V^{-4}$ for constant annoyance. Root-mean-square evaluation of vibration (i.e., $N \alpha V^{-2}$) was found to be less satisfactory. The relation for equal annoyance (V^4N = constant) is consistent with the use of the vibration dose value ($(\int_0^T a^4(t)\, dt)^{\frac{1}{4}}$) which has been proposed for vibration assessment. The relation provides an approximation of the reduction in vibration magnitude required in order to maintain the same amount of annoyance with the passage of more trains.

8.2.2 The Annoyance Produced by Simultaneous Noise and Vibration from Railways

Railway-induced building vibration usually occurs simultaneously with railway noise. The relative importance of vibration and noise is a major consideration in the event of a complaint since it is beneficial to establish which of the two stimuli is a greater source of annoyance. Section 2.6 described previous studies of the subjective equivalence of noise and vibration. There was some agreement between the results but the experiments involved vibration at magnitudes much greater than would be produced in buildings during the passage of trains. Work was required to determine the relative importance of low magnitude vibration and noise.

An experiment was conducted to determine the subjective equivalence of railway noise and vibration (see Experiment 3, Section 5.4). The results were employed to derive a relation for subjective equality. The relation was given by:

$$L_{AE} = 29.3 \log_{10} VDV + 89.2$$

where L_{AE} is the sound exposure level (dB(A)) and VDV is the vibration dose value ($ms^{-1.75}$). The findings should be of use when deciding whether the reduction of noise or the reduction of vibration would be more effective in alleviating annoyance.

It is important to consider the interaction of the effects of railway noise and vibration. Residents' reactions to vibration or noise during the passage of nearby trains may be reduced or increased by the presence of the other stimulus. A review of previous studies of the reaction to simultaneous noise and vibration was described in Section 2.7. Three studies were reported which investigated the influence of the presence of one stimulus (noise or vibration) on the assessment of the other. The results provided some evidence of an influence of noise on the assessment of vibration and of an influence of vibration on the assessment of noise. But since the investigations are few and the results are not all in agreement further work was required.

To evaluate simultaneous vibration and noise from railways with respect to the annoyance which may be caused, a method is required which provides a quantitative measure correlated with the total annoyance from a combination of the reactions to the individual stimuli. Section 2.7 discussed nine previous studies of the overall response to simultaneous noise and vibration. Only two of these fully described the derivation of a relation to predict the effects of the combined stimuli. The review showed that the methods described in previous studies are unsatisfactory. More investigations were required in this area.

Experiment 4 was conducted to investigate the interaction and the combined effects of railway vibration and noise (see Section 5.5). From the results it was concluded that railway vibration does not influence the assessment of railway noise but that, depending on the relative magnitudes of the two stimuli, the assessment of vibration may be increased or reduced by the presence of noise. Although there may be an interaction between the effects of noise and vibration when they occur together, a reasonable approximation of the relative annoyance was obtained from a summation of the effects of the individual stimuli.

8.2.3 The Frequency Dependence of Subjective Reaction to Vertical and Horizontal Whole-Body Vibration at Low Magnitudes

A method of quantifying building vibration to provide an indication of the resulting annoyance must allow for the dependence of subjective response on the frequency of the motion. Since building vibration produced by the passage of nearby trains is generally at low magnitudes, around the threshold of perception, it was necessary to determine whether frequency weightings that have been determined for high magnitude vibration are also appropriate for low magnitude vibration in buildings. Section 2.5 reviewed studies which were conducted to determine perception thresholds and comfort contours in the same experiment. There was little agreement on the effect of vibration magnitude on the frequency dependence of subjective response to whole-body vibration. Further experiments were required to determine the frequency dependence of reaction to low magnitude vibration.

Experiment 5 (see Chapter 6) was conducted to investigate the influence on annoyance of vibration frequency, vibration magnitude and vibration direction. Frequency weightings were determined for low magnitude vertical and horizontal vibration between 4 Hz and 63 Hz. The results indicated that the weightings in British Standard 6841 (1987) (W_b and W_d for vertical and horizontal motion respectively) provide a reasonable approximation of the frequency dependence of subjective response to vibration at low magnitudes. The weightings may slightly underestimate the effect of high frequency vertical motion. The subjective equivalence of vertical (z-axis) and horizontal (y-axis) motion was found to be at 5 Hz. At frequencies above 5 Hz, a given magnitude of z-axis motion was subjectively greater than the same magnitude of y-axis motion. The psychophysical relation between subjective response, ψ, and objective magnitude, φ, was determined in the form of a power function, $\psi = k\varphi^n$, where k and n are constants. The exponent, n, was independent of frequency for vertical motion but for horizontal motion the exponent increased with increasing frequency. Therefore, the frequency weightings for vertical motion were independent of vibration magnitude but for horizontal motion, the frequency weightings were magnitude dependent.

8.2.4 Prediction of the Annoyance from Complex Conditions of Simultaneous Noise and Vibration from Railways

Chapter 7 described the final experiment in which the findings of the previous experiments concerning the influence of duration, magnitude and frequency of vibration and the effect of simultaneous noise and vibration were combined to predict the relative annoyance produced by complex conditions of railway-induced building vibration and railway noise. The results of the experiment were employed to assess a general relation to be used to predict the total annoyance from simultaneous vibration and noise from railways. The relation involved the summation of the individual effects of the two stimuli and was given by:

$$\psi = 22.7 + 243\ \varphi_v^{1.18} + 0.265\ \varphi_s^{0.036}$$

where ψ is the relative annoyance caused by combined noise and vibration

φ_v is the vibration dose value ($ms^{-1.75}$)

$\log_{10} \varphi_s$ is the sound exposure level (dB(A)).

The relation allows for the influence of magnitude, frequency and duration of two stimuli. Methods based on only one of the two stimuli, i.e. either noise alone or vibration alone, were shown to be less accurate at predicting the total annoyance from simultaneous noise and vibration than the above relation which involves both stimuli. The relation provides a means of comparing the annoyance from different combinations of noise and vibration.

The findings of Experiment 6 suggest that the vibration dose value and the sound exposure level are sufficiently accurate to be useful in approximating the reaction to short exposure durations of railway vibration and noise.

8.3 RECOMMENDATIONS FOR PROCEDURES FOR ASSESSING COMBINED RAILWAY NOISE AND VIBRATION

In view of the findings of the experiments it is recommended that the following procedures are adopted to assess combinations of railway–induced building vibration and railway noise:

(i) Vibration should be assessed by determination of the vibration dose value which is given by:

$$VDV = \left(\int_0^T a^4(t)\, dt \right)^{\frac{1}{4}}$$

where a(t) is the frequency weighted acceleration in units of ms^{-2} and the time, t, is in seconds; T is the total period of time (s) during which exposure to vibration occurs.

(ii) Noise should be assessed by determination of the sound exposure level which is given by:

$$L_{AE} = 10 \log_{10} \frac{1}{t_0} \int_{t_1}^{t_2} \frac{p_A^2(t)\ dt}{p_0^2}$$

where $p_A(t)$ is the instantaneous A-weighted sound pressure; t_2-t_1 is a stated time interval long enough to encompass all significant sound of a stated event, p_0 is the reference sound pressure (2×10^{-5} Nm^{-2}), t_0 is the reference duration (1 second).

The assessment of noise by determination of the sound exposure level may not be appropriate for noise durations much greater than several minutes.

(iii) Frequency weightings for vibration should be applied as defined in BS 6841 (1987), not as in BS 6472 (1984). Measurements should be made at the interface with the body.

(iv) Axis weightings for vibration should be applied as defined in BS 6841 (1987).

(v) The relative importance of noise and vibration may be determined using the relation for the subjective equivalence which is given by:

$$L_{AE} = 29.3 \log_{10} \text{VDV} + 89.2$$

where L_{AE} is the sound exposure level (dB(A)) and VDV is the vibration dose value ($ms^{-1.75}$).

(vi) The total annoyance of simultaneous noise and vibration may be approximated by the relation given by:

$$\psi = 22.7 + 243\ \varphi_v^{1.18} + 0.265\ \varphi_s^{0.036}$$

where ψ is the subjective response to vibration and noise

φ_v is the vibration dose value ($ms^{-1.75}$)

$\log_{10} \varphi_s$ is the sound exposure level (dB(A)).

8.4 APPLICATION OF PROCEDURES FOR ASSESSING RAILWAY NOISE AND VIBRATION

This section provides examples of the application of the procedures described in Section 8.3 for determining the relative importance of railway noise and vibration and for comparing the total annoyance from combinations of railway noise and vibration.

8.4.1 The Relative Importance of Railway Noise and Vibration

The relation given in (v) of Section 8.3 (L_{AE} = 29.3 $\log_{10}$ VDV + 89.2) may be applied to a single event consisting of railway noise and vibration or to a time interval in which several trains pass. Application of the relation provides an indication of which of the two stimuli, noise or vibration, may be causing more annoyance. The noise and vibration which occurs during the time interval should be measured in terms of the sound exposure level and the vibration dose value. If the time interval contains the passage of several trains, the sound exposure level and the vibration dose value may be determined for each event separately or for the time interval as a whole. If separate measurement of each event is made, the total vibration dose value is calculated from:

$$\mathrm{VDV} = \left(\sum_{n=1}^{n=N} \mathrm{VDV}_n{}^4\right)^{\frac{1}{4}}$$

where N is the number of events during the time interval and VDV_n is the vibration dose value of a single event. The total sound exposure level is given by:

$$L_{AE} = 10 \log_{10} \left(\sum_{n=1}^{n=N} 10^{L_{AEn}/10}\right)$$

where N is the number of events during the time interval and L_{AEn} is the sound exposure level of a single event.

8.4.1.1 Noise Levels Equivalent to Vibration Limits Proposed by International and British Standards

Draft International Standard ISO 2631/DAD 1 (1980) and British Standard 6472 (1984) propose boundaries for "satisfactory conditions", "moderate complaints" and "major complaints" for continuous and intermittent vibration in terms of root-mean-square acceleration. From the corresponding vibration dose values, noise levels equivalent to these boundaries may be determined. For z-axis motion satisfactory vibration magnitudes during the day and at night in "critical working areas", e.g. hospitals, are given as 0.005 ms^{-2} r.m.s. (frequency weighted acceleration). This magnitude is described as the base curve magnitude. Different multiplying factors of the base curve are specified according to the time of day and the type of vibration and building. For residential areas during the day, BS 6472 proposes multiplying factors of two to four (ISO 2631 proposes multiplying factors of two). Hence, satisfactory magnitudes are 0.01 to 0.02 ms^{-2} r.m.s. According to BS 6472, this is the magnitude below which adverse comment or complaints are rare. A doubling of this magnitude (0.02 to 0.04 ms^{-2} r.m.s.) may result in adverse comment or moderate complaints, and a quadrupling (0.04 to 0.08 ms^{-2} r.m.s.) may result in significant adverse comment or major complaints. These boundaries usually apply to a 16-hour period. The corresponding estimated vibration dose values (EVDV = $((1.4 \times \text{r.m.s.})^4 \times t)^{\frac{1}{4}}$) are shown in Table 8.1.

	Estimated Vibration Dose Values ($ms^{-1.75}$)	
	Multiplying Factor	
	2	4
Rare Complaints	0.217	0.434
Moderate Complaints	0.434	0.868
Major Complaints	0.868	1.736

Table 8.1 Estimated vibration dose values corresponding to boundaries proposed in BS 6472 (1984) and ISO 2631/DAD 1 (1980).

The equivalent vibration magnitude, a_t (ms^{-2} r.m.s.), for any other period, t seconds, is then given by:

$$a_t = \frac{EVDV_{16h}}{1.4 \times t^{\frac{1}{4}}}$$

The relation for the subjective equivalence of noise and vibration was determined from stimuli of durations of less than 29 seconds. Therefore, it may not be applicable to exposure durations much greater than several minutes. However, it is of interest to apply the relation to long durations as well as to short durations. Table 8.2 shows the sound exposure levels equivalent to the vibration boundaries proposed in BS 6472 (1984) and ISO 2631/DAD 1 (1980) according to the equivalence curves from Experiments 3, 4 and 6. The corresponding sound pressure levels and r.m.s. acceleration magnitudes for 10 seconds and 24 hours (i.e. for a single event and for all day) are also provided. Section 7.4 discussed the differences between the three relations for the subjective equivalence of noise and vibration which were determined in Experiments 3, 4 and 6. It was concluded that the relation determined from the results of Experiment 3 may be most accurate (L_{AE} = 29.3 $\log_{10}$ VDV + 89.2). The recommended procedures for assessing railway vibration and noise (see Section 8.3) therefore proposes use of the relation from Experiment 3 for determination of the relative importance of the two stimuli. However, Table 8.2 includes figures for the other two relations for comparative purposes. For the boundary corresponding to rare complaints, there is approximately a 5 dB difference between the sound levels from the relations of Experiments 3 and 4 and of Experiments 4 and 6. This is a clearly perceptible difference. For the boundary corresponding to major complaints, there is approximately a 7 dB difference between the sound levels from the relations of Experiments 3 and 4 but for Experiments 4 and 6 the sound levels are almost equal. The differences between the boundary sound levels obtained from the three relations are such that further investigations would be of value to establish that the relation from Experiment 3 is the most appropriate.

Although International and British Standards have proposed vibration limits, there exist no equivalent limits for noise, nor is there a uniform method of determining community reaction to intruding noise. Various levels have been proposed. For example, the Greater London Council planned to propose that noise levels at the facade of a house of up to 65 dB $L_{Aeq,24h}$ would be acceptable. Assuming the attenuation of a building to be 20 dB this would be 45 dB $L_{Aeq,24h}$ inside a house. The United States Department of Housing and Urban Development suggested indoor noise levels should not exceed 45 dB(A) for more than eight hours per 24 hours i.e. 40 dB $L_{Aeq,24h}$. The United States Environmental Protection Agency recommended community noise levels of 45 dB $L_{Aeq,24h}$ for adequate protection against indoor activity interference and annoyance.

The noise levels given in Table 8.2, which according to Experiments 3, 4 and 6 are equivalent to acceptable vibration magnitudes, are lower than might be expected when the various proposed noise limits are considered. The recommendation of future work in this area is included in Section 8.5.4.

Boundary	Vibration Magnitudes	Noise Levels dB(A)		
		Experiment 3 $L_{AE}=29.3\log_{10}VDV+89.2$	Experiment 4 $L_{AE}=26.7\log_{10}VDV+81.7$	Experiment 6 $L_{AE}=32.4\log_{10}VDV+89.6$
Rare Complaints	EVDV=0.217 $ms^{-1.75}$ a_{10s} = 0.087 ms^{-2} r.m.s. a_{24h} = 0.009 ms^{-2} r.m.s.	SEL = 69.8 SPL 10s = 59.8 SPL 24h = 20.4	SEL = 64.0 SPL 10s = 54.0 SPL 24h = 14.6	SEL = 60.1 SPL 10s = 50.1 SPL 24h = 10.7
Moderate Complaints	EVDV = 0.434 $ms^{-1.75}$ a_{10s} = 0.174 ms^{-2} r.m.s. a_{24h} = 0.018 ms^{-2} r.m.s.	SEL = 78.6 SPL 10s = 68.6 SPL 24h = 29.2	SEL = 72.0 SPL 10s = 62.0 SPL 24h = 22.7	SEL = 69.9 SPL 10s = 59.9 SPL 24h = 20.5
Major Complaints	EVDV = 0.868 $ms^{-1.75}$ a_{10s} = 0.349 ms^{-2} r.m.s. a_{24h} = 0.036 ms^{-2} r.m.s.	SEL = 87.4 SPL 10s = 77.4 SPL 24h = 38.0	SEL = 80.1 SPL 10s = 70.1 SPL 24h = 30.7	SEL = 79.6 SPL 10s = 69.6 SPL 24h = 30.2

Table 8.2 Vibration magnitudes and equivalent noise levels corresponding to boundaries proposed in BS 6472 (1984) and ISO 2631/DAD 1 (1980).

8.4.2 The Total Annoyance from Combined Railway Noise and Vibration

The relation for the effects of combined noise and vibration determined from the results of Experiment 6 is given by:

$$\psi = 22.7 + 243\ \varphi_V^{1.18} + 0.265\ \varphi_S^{0.036} \qquad (8.1)$$

where φ_v is the vibration dose value ($ms^{-1.75}$) and $\log_{10} \varphi_s$ is the sound exposure level (dB(A)).

The relation can be employed to compare the annoyance which may be caused by different combinations of railway-induced building vibration and railway noise. The relative annoyance produced by the passage of different trains may be compared by measurement of the sound exposure level and the vibration dose value of each event. Substitution of the vibration and noise levels into Equation 8.1 yields a value linearly correlated with the annoyance caused by an event. For example, if a first event consists of noise at a sound exposure level of 60 dB(A) and vibration at a vibration dose value of 0.10 $ms^{-1.75}$, Equation 8.1 yields a value of 77 for the subjective response. A second event may result in a sound exposure level of 70 dB(A) and a vibration dose value of 0.20 $ms^{-1.75}$. This corresponds to a subjective value of 147 which is a factor of 1.9 times greater than the subjective value of the first event. Thus, the second event will be expected to have caused almost twice the annoyance caused by the first event. Similarly, the same method may be employed to compare the annoyance from different time intervals containing the passage of several trains.

8.5 RECOMMENDATIONS FOR FUTURE RESEARCH

8.5.1 Effect of Temporal Separation of Passing Trains

Experiments 1 and 2 (see Chapter 4) were conducted to investigate the annoyance produced by a one-hour session during which vibration from the passage of a single train was reproduced 4, 8, 16 or 32 times at equal intervals. Corbridge (1982) conducted a study designed to assess the response of seated subjects to impulsive vertical (z-axis) vibration. Subjects assessed the discomfort of sinusoidal test motions containing various numbers of impulses. The motions had the same root-mean-square and root-mean-quad acceleration magnitudes and differed only in the temporal arrangements of the impulses. The duration of each motion was 23 seconds and the separation between impulses varied between zero and five seconds.

The results indicated that the subjective response increased as the separation between impulses was increased from 0 to 0.625 seconds. Increasing the separation beyond this time period had little effect on the discomfort. The study involved much smaller time intervals than occur between the passage of trains and so the results may not be applicable to railway noise and vibration. Trains pass at regular or irregular intervals and the time between trains may vary considerably. Therefore, it would be of value to conduct a study similar to that conducted by Corbridge to investigate whether the annoyance from stimuli consisting of repetitions of railway vibration and noise with the same vibration dose values and sound exposure levels depends on the temporal separation of the events.

8.5.2 Perception Thresholds

Since railway-induced building vibration generally occurs at very low magnitudes, determination of reaction to the vibration must involve consideration of whether the motion is perceptible. A review of investigations of the threshold of perception of translational whole-body vibration is described in Section 2.4. Only a small number of studies have been conducted to investigate the perception threshold of recumbent subjects and there is little agreement between the findings of the studies. Further investigations of the threshold of recumbent subjects would be beneficial since residents in close proximity to railway lines may be exposed to vibration while sleeping.

8.5.3 The Time Dependency of Subjective Reaction to Noise

The trade-off between vibration duration and vibration magnitudes has been investigated for exposure durations of up to one hour. The results supported the use of the vibration dose value (see Chapter 3, Experiments 1 and 2). A corollary of this finding might be that the vibration dose value is not only applicable to the evaluation of vibration from the passage of a single train but also to longer duration exposures of up to at least one hour consisting of many events. The results of Experiments 3, 4 and 6 indicate that the sound exposure level provides a useful means of evaluating short exposure durations of railway noise, such as from the passage of a single train. However, the experiments only involved single noise events. Previous investigations of the time dependency of subjective reaction to noise have also usually involved durations of up to only about one minute, e.g. Kryter and Pearsons (1963), Pearsons (1966) (see Appendix 5.1). Although the results of Experiments 3, 4 and 6 suggest that the sound exposure level can be used to evaluate single noise events, it may not be appropriate for exposure durations much greater than several minutes. Further investigations are required to determine the time dependency of reaction to longer exposure durations of noise. This would provide an indication of whether the sound exposure level should be employed to evaluate time periods containing noise from the passage of many trains.

8.5.4 The Relative Importance of Noise and Vibration

The subjective equivalence curve obtained from the results of Experiment 3 corresponds to noise levels equivalent to vibration which are about 6 dB and 10 dB greater than the equivalence curves from Experiments 4 and 6 respectively. These differences are discussed in Section 7.4 and it is concluded that the differences between the equivalence curves may be attributed to differences in the ranges of noise levels and to different experimental techniques. It is suggested that the results of Experiment 3 are less likely to have been subject to biases and therefore it is tentatively proposed that the equivalence curve of Experiment 3 may be more appropriate ($L_{AE} = 29.3 \log_{10} VDV + 89.2$). However, further investigations would be of value to verify which relation most accurately describes the subjective equivalence of railway vibration and noise.

8.5.5 The Frequency Dependence of Reaction to Vibration at Low Magnitudes

Previous studies, e.g. Miwa (1967) and Griffin, Whitham and Parsons (1982), have indicated that there is little difference in the response to fore-and-aft (x-axis) and lateral (y-axis) vibration. However, most of the studies have involved motion at higher magnitudes than would be experienced in buildings. Experiment 3 was conducted to determine the frequency dependence of annoyance from vertical (z-axis) and lateral (y-axis) whole-body vibration at low magnitudes. Reaction to fore-and-aft (x-axis) motion was not investigated since it was assumed that the frequency dependence at low magnitudes is the same as for lateral (y-axis) motion. The validity of this assumption may be further investigated.

The results of Experiment 3 (see Chapter 6) indicate an increase in sensitivity as the frequency increases from 50 Hz to 63 Hz. Some stimuli at 63 Hz were imperceptible to some subjects and there was a significant amount of cross-axis coupling. Therefore, it may be appropriate to exercise caution when considering the evidence of an increase in sensitivity at 63 Hz. Weightings for low magnitudes of high frequency vibration merit further investigation.

Residents adopt sitting, standing or recumbent postures during exposure to railway-induced vibration. The frequency dependence of the reaction of seated subjects was investigated in Experiment 3. Future work may involve examination of the frequency dependence of the reaction of standing and recumbent subjects to horizontal and vertical vibration at low magnitudes.

8.5.6 Visibility of Passing Trains

Future laboratory experiments involving the observation of railways combined with exposure to railway noise and vibration would provide information on the dependence on visibility of annoyance due to passing trains. The results should be valuable when considering methods of reducing complaints of residents to railway vibration or noise. If an interaction occurs between visibility and reaction to noise and vibration, annoyance may be reduced by ensuring that the view of passing trains is eliminated.

8.5.7 Field Studies

The present study has involved a series of experiments conducted in the laboratory. The aim of the study was to determine a method of predicting human response to combined vibration and noise measured within buildings adjacent to railways. Therefore, further investigations should involve field studies which relate annoyance to vibration and noise according to the methods evolved from this study. The field studies could involve the selection of sites in close proximity to railway lines where noise and vibration are perceptible and where complaints about railway noise and/or vibration have been reported. Verification of the findings of this study would involve correlation of annoyance with measurements of noise and vibration using the methods evolved. Field studies may allow correlation of different combinations of vibration and noise with absolute measures of annoyance. This would enable recommendations to be made of acceptable magnitudes of railway-induced building vibration and railway noise.

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APPENDIX 2

DEFINITION OF SOUND EXPOSURE LEVEL, L_{AE}

The sound exposure level was originally employed to describe the overflight noise exposure from individual aircraft. It can be applied to single events as well as to noise of a continuous character. The sound exposure level provides a measure of A-weighted sound exposure in decibels which allows for the effect of magnitude and frequency of the sound. In this scale 0 dB corresponds to the reference sound pressure 2 x 10^{-5} Nm^{-2} continuing for a duration of 1 second. The sound exposure level is given by:

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

where $p_A(t)$ is the instantaneous A-weighted sound pressure,

t_2-t_1 is a stated time interval long enough to encompass all significant sound of a stated event,

p_0 is the reference sound pressure (2 x 10^{-5} Nm^{-2}),

t_0 is the reference duration (1 second).

APPENDIX 4.1

INSTRUCTIONS TO SUBJECTS FOR EXPERIMENT 1, PART 1 AND EXPERIMENT 2

You will shortly be presented with vibrations which might occur in a house. After experiencing the vibrations for one hour you will be asked to indicate the annoyance they would have caused if they had occurred in your own sitting-room. Please make your judgement by considering the session as a whole.

Annoyance which would have been caused by the vibration in your own sitting-room.

Not annoyed	0
	1
	2
	3
	4
	5
Extremely annoyed	6

APPENDIX 4.2

INSTRUCTIONS TO SUBJECTS FOR EXPERIMENT 1, PART 2

You will now be presented with some further vibrations which might occur in a house. After experiencing each motion you will be asked to indicate the annoyance it would have caused if it had occurred in your own sitting-room. Please make your judgement by considering each vibration separately.

Annoyance which would have been caused by the vibration in your own sitting-room.

Not annoyed	0
	1
	2
	3
	4
	5
Extremely annoyed	6

APPENDIX 4.3

RESULTS OF EXPERIMENT 1: THE EFFECT ON ANNOYANCE OF THE NUMBER OF PASSING TRAINS AND THE MAGNITUDE OF VIBRATION

MALE (M) OR FEMALE (F)	SUBJECT NUMBER	PART 1 REGRESSION EQUATION RELATING MAGNITUDE (ms^{-2} r.m.s.) AND ANNOYANCE	
		INTERCEPT	GRADIENT
M	1	0.5717	25.803
M	2	1.0190	23.044
M	3	1.7335	18.879
F	4	-0.1976	26.074
F	5	1.0478	34.296
F	6	1.1800	37.109
M	7	0.8418	17.364
M	8	-0.6744	38.570
M	9	0.0098	26.669
F	10	-0.4332	18.879
F	11	1.1371	22.558
F	12	-0.1399	10.116
M	13	-0.6793	31.646
M	14	1.5014	9.304
M	15	0.3565	25.316
F	16	2.5112	23.153
F	17	2.4740	20.177
F	18	-0.1737	30.401
M	19	-0.3938	10.170
M	20	-0.0752	40.679
M	21	-0.8572	21.313
F	22	0.4360	12.550
F	23	-0.3003	26.344
F	24	-0.4768	25.316
M	25	2.4761	21.313
M	26	0.2925	25.046
M	27	0.3903	17.851
F	28	0.9712	27.210
F	29	1.8713	33.268
F	30	-0.1660	30.293
M	31	0.0162	30.077
M	32	-0.3066	22.936
M	33	1.8565	12.496
F	34	-0.2194	22.882
F	35	-0.5696	26.615
F	36	0.2335	18.879
M	37	-0.2046	43.655
M	38	1.2658	14.930
M	39	0.6104	38.083
F	40	2.7975	31.970
F	41	-1.1638	44.250
F	42	-0.3811	16.986
M	43	3.4592	25.046
M	44	0.0513	31.916
M	45	-1.2229	38.083
F	46	-0.2665	31.700
F	47	0.1069	27.642
F	48	-0.3706	22.666

APPENDIX 4.3 continued

MALE (M) OR FEMALE (F)	SUBJECT NUMBER	PART 2 EFFECT OF NUMBER OF TRAINS		
		NUMBER OF TRAINS	ANNOYANCE RATING	EQUIVALENT MAGNITUDE (ms^{-2} r.m.s.)
M	1	4	2	0.0553
M	2	4	1	-0.0008
M	3	4	2	0.0141
F	4	4	1	0.0459
F	5	4	2	0.0278
F	6	4	3	0.0490
M	7	4	1	0.0091
M	8	4	4	0.1212
M	9	4	1	0.0371
F	10	4	1	0.0759
F	11	4	2	0.0382
F	12	4	1	0.1127
M	13	8	1	0.0531
M	14	8	1	-0.0539
M	15	8	1	0.0254
F	16	8	2	-0.0221
F	17	8	4	0.0756
F	18	8	2	0.0715
M	19	8	0	0.0387
M	20	8	2	0.0510
M	21	8	0	0.0402
F	22	8	1	0.0449
F	23	8	1	0.0494
F	24	8	2	0.0978
M	25	16	3	0.0246
M	26	16	2	0.0682
M	27	16	3	0.1462
F	28	16	4	0.1113
F	29	16	5	0.0940
F	30	16	1	0.0385
M	31	16	1	0.0327
M	32	16	1	0.0570
M	33	16	2	0.0115
F	34	16	1	0.0533
F	35	16	1	0.0590
F	36	16	1	0.0406
M	37	32	4	0.0963
M	38	32	1	-0.0178
M	39	32	4	0.0890
F	40	32	3	0.0063
F	41	32	3	0.0941
F	42	32	3	0.1991
M	43	32	6	0.1014
M	44	32	3	0.0924
M	45	32	2	0.0846
F	46	32	4	0.1346
F	47	32	2	0.0685
F	48	32	2	0.1046

APPENDIX 5.1

EVALUATION METHODS FOR NOISE

A5.1.1 Introduction

Chapters 5 and 7 describe experiments concerned with the subjective reaction to simultaneous noise and vibration. The experiments investigated the relative importance of railway noise and vibration and the interaction of the effects of the two stimuli. A means of describing the noise stimuli is required which may be related to the noisiness or annoyance value of the noise.

The aim of this appendix is to find a suitable evaluation method for railway noise. This involves consideration of the various methods currently in use for expressing the annoyance value attributed to different types of noise. Assessment of these methods involves examination of the time dependency and the effect of frequency and magnitude on the reaction to noise.

A5.1.2 Current Indices and Scales for Community Reaction to Noise

At present there is no uniform system for determining community reaction to environmental noise. A multiplicity of units, scales and indices are currently used to evaluate the various types of noise originating from different sources. This section describes some of the evaluation methods.

The equivalent continuous noise level, L_{Aeq}, has become the basic measurement for community noise as well as other types of noise. It is the value of A-weighted sound pressure level of a continuous steady sound that, within a specified time interval (T), has the same mean square sound pressure as a sound under consideration whose level varies with time. The equivalent continuous noise level, in decibels, is given by:

$$L_{Aeq,T} = 10 \log_{10} \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right]$$

where T is the total exposure duration of a sound starting at t_1 and ending at t_2; p_0 is the reference sound pressure (2×10^{-5} Nm^{-2}) and $p_A(t)$ is the instantaneous

A-weighted sound pressure of the sound signal. Use of the A-weighted equivalent continuous noise level is recommended by the International Organization for Standardization (ISO R 1996, 1971) for describing industrial noise.

Griffiths and Langdon (1968) conducted a social survey from which they hypothesised that dissatisfaction towards traffic noise expressed by residents depends on the variability of the noise. Griffiths and Langdon derived the traffic noise index (TNI) to correlate with dissatisfaction. TNI is given by:

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30$$

where L_{10} is the sound pressure level (dB(A)) of noise exceeded 10% of the time and L_{90} is the sound pressure level (dB(A)) of the noise exceeded 90% of the time. L_{10}-L_{90} corresponds to the variation in noise level. L_{90} corresponds to the background noise level. Another index for quantifying traffic noise is the average value of L_{10} in dB(A), for each hour between 0600 and 2400, on a normal working day. This index, L_{10} (18 hour), has been shown to give as good a correlation with dissatisfaction as TNI.

There have been many attempts to formulate criteria for the prediction of aircraft noise annoyance in the community. The attempts have resulted in various indices. The noise and number index (NNI) (H.M.S.O., 1963) was derived from social survey data and is given by:

$$NNI = L_{PNmax} + 15 \log_{10} N - 80$$

where L_{PNmax} is the logarithmic average of the maximum perceived noise levels during the passage of successive aircraft, and N is the number of aircraft heard in the defined daytime period.

The perceived noisiness describes the degree of annoyance or noisiness of a sound. In parallel with the use of the sone for loudness, the noy has become the subjective unit of noisiness. A sound with a frequency centred at 1 kHz and a sound pressure level of 40 dB has a noisiness of 1 noy. A sound which is twice as noisy is rated at 2 noys. From the concept of perceived noisiness, the rating scale of perceived noise level, in decibels, was developed. The noisiness, N, in noys is converted into perceived noise level, L_{PN}, in decibels using the following expression (BS 5727, 1979):

$$L_{PN} = 40 + \frac{10 \log_{10}N}{\log_{10}2}$$

A survey of railway noise in Great Britain was conducted by Fields and Walker (1978) from which it was estimated that 2% of the population of England was bothered by railway noise. The results of the survey suggested that 24 hour L_{Aeq} was as closely related to annoyance as any other accepted noise descriptor. The combination of noise level and number of events incorporated in L_{Aeq} appeared to be necessary. Only two other studies have been conducted to investigate community response to railway noise. Nimura, Sone and Kono (1973) propounded that for high speed trains it was satisfactory to describe noise in terms of the maximum A-weighted sound pressure level during the passage of the train. From the results of a study conducted in 1973, Aubree proposed that the equivalent continuous sound level, L_{Aeq}, was an adequate scale to describe railway noise with respect to annoyance.

Robinson (1977) compared the units and indices currently employed to describe noise levels and noise exposure and he discussed the feasibility of a unified system. Robinson questioned whether it was reasonable for the existence of such a variety of units for the physical and auditory magnitude of sounds (e.g. dB(A), dB(B), dB(C), dB(D), dB(PN), phon, sone) and so many noise exposure measures (e.g. CNR, NEF, NNI, L_{Aeq}, L_{10}, L_{dn}, L_{EPN}, L_{AE}). Currently air traffic may be evaluated in terms of NNI (although not for helicopters). Continuous events, such as road traffic noise, may be described by L_{10} or L_{Aeq}. However, it is not clear which measure may be used for a combination of these noise sources since the different measures are not additive. When both traffic noise and aircraft noise, for example, are present, difficulties arise since L_{10} cannot be applied to aircraft noise and NNI is meaningless when applied to traffic noise. Robinson (1977) suggested that a single measure of noise exposure might suffice. He pointed out that L_{Aeq} has some very attractive characteristics. It is a measure of acoustic energy received and therefore has simple additive properties not shared by other physical quantities. It allows for the duration of the exposure, providing a time averaged sound pressure level over a specified period. Its physical properties are attractively simple. Robinson argued that pursuit of better units may be unnecessary since the instability of human reaction implies coarser discrimination between two noise situations than the uncertainty with which L_{Aeq} reflects such comparisons.

A5.1.3 The Time Dependency of Subjective Reaction to Noise

Kryter and Pearsons (1963) stated that it is important to differentiate between loudness and noisiness (or annoyance) when considering the time dependency of reaction to sound. They made reference to some studies which indicate a very different effect of varying the duration of a sound on the loudness than on the noisiness (e.g. Garner (1949), Egan (1955)).

Stevens and Pietrasanta (1957) proposed that the acceptability of aircraft sounds may be estimated by measuring the total energy of the sound. This is in accordance with the use of the equivalent continuous noise level, L_{Aeq}, which is derived from the concept that equal amounts of acoustic energy will produce equal reaction. This implies that a doubling of the duration of a sound has the same effect as increasing its level by 3 dB. Kryter and Pearsons (1963) conducted an experiment to determine the trade-off between intensity level and duration with respect to noisiness. The method of paired comparisons was employed. Fourteen subjects were asked to judge whether the first or second of a pair of sounds was noisier. The stimuli consisted of helicopter, propeller, jet and narrow band noise. The results showed that, over a range of durations from 1.5 to 12 seconds, a doubling of sound duration corresponded to the same increase in noisiness as an increase in sound pressure level of 4.5 dB.

A similar experiment was conducted by Pearsons (1966) which involved the presentation, to 18 subjects, of simulated aircraft noise ranging in duration from 4 to 64 seconds. The results suggested a doubling of duration corresponds to an average increase in sound intensity of 2.5 dB. Pearsons (1966) combined these results with those of the earlier study by Kryter and Pearsons (1963) and suggested a single line would not adequately describe the trade-off between sound intensity and duration. He propounded that the effect of duration on perceived noisiness might be a monotonic function of duration, with a continuously decreasing slope. The combined results were approximated by three lines for three duration ranges. The effect of duration was approximated by 6 dB per doubling of duration for 1.5 to 4 seconds and by 3.5 dB per doubling of duration for 4 to 16 seconds. For 16 to 64 seconds a slope of 2 dB per doubling of duration was considered appropriate.

Robinson (1971) devised a formula, termed the "noise pollution level", for a unified system of noise assessment. The method evolved from three observations: the influence of the energy principle due to its attractive physical characteristics; evidence that increasing the duration of noise events caused annoyance to increase at a higher rate than accounted for by the energy principle; greater disturbance caused by fluctuating acoustic environments than general loudness. Robinson adapted the energy principle to produce the noise pollution level which is based on two terms. One term, the equivalent continuous noise level, L_{eq}, represents the energy principle. A second term allows for an increase in annoyance when fluctuations of the noise level occur. The noise pollution level is given by:

$$L_{NP} = L_{eq} + k\,\sigma$$

where L_{eq} is the "energy mean" of the noise level over a specified duration, σ is the standard deviation of the instantaneous level and k is a constant which is provisionally assigned the value 2.56. The first term, L_{eq}, is largely governed by the intensity of the loudest intruding noises and the second term is greatly influenced by the background noise. Robinson specified that the noise level, L, was to be measured on a scale adequately related to subjective noisiness, e.g. dB(A), dB(D), dB(PN). He stated that it was not necessary nor realistic at that time to restrict the L_{NP} formula to one unit. The noise pollution level was applied to road traffic and aircraft noise annoyance data obtained in field studies (Griffiths and Langdon (1968), McKennell (1963)) and to laboratory studies investigating the trade-off between duration and sound intensity (Kryter and Pearsons (1963), Pearsons (1966)). Robinson concluded that the noise pollution level correctly predicted the trade-off between sound intensity and duration and provided an index which can be applied to aircraft, road traffic and railway noise and to mixed environments. The index appeared to correlate well with the subjective results but Robinson judged that although the L_{eq} term seemed to have an obvious place in the formula, the other term, 2.56σ, and the manner in which the two terms were combined may have needed some revising.

A5.1.4 The Effect of Frequency on the Annoyance of Noise

The A, B and C frequency weightings were based on approximations to 40, 70 and 90 phon loudness levels derived by Fletcher and Munson (1933). They were originally used for the measurement of sound in three ranges: less than 55 dB, 55 to 80 dB, and greater than 80 dB for A, B and C weightings respectively. The A frequency weighting has become popular due to its success in the field of subjective acoustics and because it provides an uncomplicated method of measuring and assessing noise. The A weighting has been found to correlate well with subjective reaction at high noise levels as well as at levels less than 55 dB. With the exception of aircraft noise, the A weighting is used almost universally for noise measurement (see Robinson, 1976).

A5.1.5 The Dependence of Loudness on Noise Intensity

The psychophysical power function describing the subjective magnitude of noise has been investigated by many experimenters. Over the middle and high stimulus ranges the power function provides an accurate description of the subjective loudness scale. However, the results of some studies indicate that at levels near threshold the power function is less satisfactory. Galanter and Messick (1961) suggested that the loudness function may be more closely approximated by one of two forms consisting of a power function with an additive constant. The two functions were given by:

$$\psi = k\varphi^n + b \qquad (A5.1.1)$$

and

$$\psi = k(\varphi + b)^n \qquad (A5.1.2)$$

where k, b and n are constants. The constant in the relation given by Equation A5.1.1 was used to translate the dependent variable. McGill (1960) interpreted this constant as the stretching or shrinking of the "elastic ruler" used by the subjects to measure the loudness of a stimulus. The constant in Equation A5.1.2 may be interpreted as a threshold parameter that translates the zero point of the physical scale. Galanter and Messick found that either of the two functions was an improvement over the power function ($\psi = k\varphi^n$). On the basis of further analysis they advocated the use of the function given by Equation A5.1.2.

Stevens (1957) also discussed the addition of a constant to the power function. He suggested that the constant makes allowance for the inevitable residual "noise level" in the perceptual system. Stevens pointed out that if this form of noise function were accepted, the resulting equations and deviations would become more complicated but the conclusions to which the relation leads would not be altered. Since the value of the constant is small its addition significantly affects the function only at low noise levels.

The value of the exponent, n, in the power function, $\psi = k\varphi^n$, has been investigated by many experimenters. The variability of the results obtained seems to depend on the experimental technique (Kryter, 1970). The method of equal intervals or equisection requires a subject to adjust the level of a third tone so that the difference between the levels of the third and second tone is the same as the difference between the second and first tone. The results obtained from studies which have employed the method of equal intervals are in close agreement. In contrast, the method of magnitude estimation has resulted in widely differing exponents. Garner (1958, 1959) concluded that subjects using the method of magnitude estimation will give different judgements on which noise level appears half as loud when they know the range of levels available than when they do not.

In the 1930's physicists and psychologists conducted many experiments to elicite ratio judgements of loudness. There was fairly good agreement between the results and the power form of the loudness function became established. In 1955 Stevens examined all the data then available to determine an exponent for the power law. Entries from 178 studies provided a median decibel change in sound pressure level of ten corresponding to a loudness ratio of 2:1. The exponent in the power function relating loudness, ψ_s, to sound pressure, p, then becomes 0.600, i.e. $\psi_s = kp^{0.600}$. A value of 0.600 seems to have been generally accepted as the growth function of loudness. In 1957 Robinson reanalysed and compared the results of 12 studies which sought to investigate the subjective loudness scale. Robinson concluded that a reasonably accurate approximation of the results could be described by a two-fold loudness change corresponding to a 10 dB interval in sound pressure level. This supports a value of 0.600 for the exponent. However, in 1971 Stevens pointed out that since 1955 an abundance of evidence had accumulated which suggested that the value of the loudness exponent is a little higher than 0.600. Stevens (1966) conducted ten cross-modality experiments. In each, noise was matched to another stimulus, for example, electric current, vibration, brightness. The exponent for each of the ten perceptual continua had been determined in other experiments so the loudness exponent could be estimated from the slope of the equal-sensation functions. The ten estimates gave an average loudness exponent of 0.678 and a median loudness exponent of 0.665. Cross-modality matching was conducted by Moskowitz (1968). Subjects assigned numbers to indicate judgements of loudness and of taste intensity. The results indicated a mean of 0.676 for the exponent for noise. Stevens and Marks (1965) conducted experiments which involved the adjustment of brightness to match loudness and the adjustment of loudness to match brightness, thus cancelling any regression effect. The slope of the equal sensation function was unity. Since the brightness exponent is $^1/_3$, this indicated a value of $^2/_3$ for the loudness exponent, i.e. 0.667. The regression effect occurs in all matching experiments and may be considered as the tendency for the subjects to shorten the range of whichever variable they are allowed to adjust. Interchanging the fixed and the adjustable stimuli when conducting cross-modality matching allows the determination of an average exponent while minimising the regression effect. According to Stevens (1971), between 1953 and 1971 many studies employed the method of magnitude estimation to investigate the loudness scale. However, magnitude estimation tends to result in underestimation of the exponent because of the regression effect.

Stevens (1971) examined the evidence from previous studies for the value of the loudness exponent and decided to propose a calculation procedure (Mark VII) for the perceived level of loudness or noisiness based on an exponent of $^2/_3$. This suggests that the perceived magnitude doubles with each increase of 9 dB. Therefore, the psychophysical power function relating perceived sound magnitude, ψ_s, and sound pressure, p, is given by:

$$\psi_s = kp^{0.667}$$

from which $$\log \psi_s = 0.667 \log p + \log k$$

Since sound pressure level, SPL, is given by:

$$SPL = 20 \log_{10} \left[\frac{P_{rms}}{P_{ref}}\right]$$

then $$\log_{10} \psi_s = 0.667 \frac{SPL}{20} + \log_{10} k$$

Therefore, the relation between subjective magnitude, ψ_s, and sound pressure level, SPL, is given by:

$$\log_{10} \psi_s = 0.033 \ SPL + \log_{10} k$$

A5.1.6 The Relation Between Loudness and Noisiness

Stevens (1971) compared the results of 25 studies in which frequency weightings for sound were determined. The studies determined noisiness (or annoyance) contours which were similar to loudness contours. Comparison of the contours indicated that some studies indicated a difference between loudness and noisiness while others did not. Stevens concluded that a single composite weighting function is adequate for the evaluation of noise.

A5.1.7 Discussion and Conclusions

The studies discussed in this appendix, which have considered the time dependency of subjective reaction to noise, have mainly been concerned with aircraft noise and with exposure durations of less than 1 minute. These studies indicate a time dependency which is approximated by an increase in level of 3 dB having the same effect on subjective reaction as a doubling in the duration of a sound. This is in accordance with the use of the equivalent continuous noise level. Since a single railway noise event persists for a similar duration to a single aircraft noise event, it seems reasonable to propound that the equivalent continuous noise level may also be appropriate for assessing single events of railway noise. However, further investigations are required before it can be established whether the equivalent continuous noise level is appropriate for long exposure durations containing many railway noise events. Previous studies indicate the value of 0.600 approximates the value of the exponent in the power function for noise, i.e., the growth function of loudness as a function of noise intensity is 0.600. However, a value of 0.667 may be more appropriate.

This appendix has shown that the equivalent continuous noise level, L_{Aeq}, is generally a satisfactory method of quantifying environmental noise, including railway noise. L_{Aeq} encorporates the A frequency weighting which has been widely established.

When a noise environment is a result of a number of identifiable noise events, International Standard 1996/1 - 1982(E) recommends that the equivalent continuous noise level, $L_{Aeq,T}$, may be calculated from the sound exposure levels of the individual events occurring during a time period, T:

$$L_{Aeq,T} = 10 \log_{10} \left[\frac{t_0}{T} \sum_{i=1}^{n} 10^{0.1 L_{AEi}} \right]$$

where L_{AEi} is the sound exposure level of the ith event in a series of n events in time period, T, in seconds, and t_0 is 1 second. The sound exposure level, L_{AE}, is defined in Appendix 2 and may be considered as the value of L_{Aeq} for a single noise event referred to a total time of 1 second. L_{AE} and L_{Aeq} encompass the same trade-off between exposure duration and sound level and the same frequency dependence. While L_{Aeq} provides a time averaged sound pressure level over a specified period, L_{AE} increases with increasing exposure duration and therefore provides an accumulative measure of sound exposure or a dose. The sound exposure level is, therefore, suitable for the assessment of noise from single short duration events, such as the passage of trains. Noise stimuli presented in the experiments described in this thesis are therefore quantified in terms of the sound exposure level, L_{AE}.

APPENDIX 5.2

INSTRUCTIONS TO SUBJECTS FOR EXPERIMENT 3

You will be presented with many different types of vibration and noise which might occur in a house.

After experiencing each combination please state whether you would prefer the vibration or the noise to be reduced if they were to occur together in your own sitting-room. Say "vibration" if you would prefer the vibration to be reduced or say "noise" if you would prefer the noise to be reduced.

Then use the following scale to indicate the total annoyance that would have been caused if the combination of noise and vibration had occurred in your own sitting-room.

Not annoyed	0
	1
	2
	3
	4
	5
Extremely annoyed	6

APPENDIX 5.3

INSTRUCTIONS FOR PRACTICE SESSION OF EXPERIMENT 4

This experiment requires to assign numbers corresponding to the annoyance caused by different noise and vibration stimuli.

In order to give you some practice using this technique you will first assign numbers to lines according to their length. The first line shown to you will be assigned a value of 100. Your task will be to assess the length of other lines with reference to the first.

For example, if the second line you are presented with appears to be 4 times the length of the first it should be assigned a value of 400. Alternatively, if it appears to be only ¼ of the length of the first it should be assigned the value of 25.

APPENDIX 5.4

INSTRUCTIONS TO SUBJECTS FOR SESSION A, EXPERIMENT 4

You will be presented with many different types of vibration and noise which might occur in the house. Your task will be to assign numbers to each stimulus.

For the first stimulus you will receive, the vibration will be assigned the value of 100. After each of the following stimuli please assign a number to indicate the annoyance that the vibration would cause if the stimuli were to occur in your own sitting-room.

Try to make the ratio between the numbers you assign correspond to the ratio between the annoyance caused by each stimulus. For example, if you consider a stimulus would be twice as annoying as a stimulus which has been assigned the value of 100, you should assign it the value of 200. Alternatively, if you consider it to be only half as annoying you should assign it the value of 50.

Remember to base your judgement on the vibration alone and not on the noise.

After receiving the first stimulus, assigned the value of 100, you will be presented with four practice stimuli. You will then be given an opportunity to ask questions before starting the experiment. This will also begin with the stimulus assigned the value of 100.

Please sit in the same comfortable upright posture throughout the experiment and keep your feet and legs as still as possible.

APPENDIX 5.5

INSTRUCTIONS TO SUBJECTS FOR SESSION B, EXPERIMENT 4

You will be presented with many different types of vibration and noise which might occur in the house. Your task will be to assign numbers to each stimulus.

For the first stimulus you will receive, the noise will be assigned the value of 100. After each of the following stimuli please assign a number to indicate the annoyance that the noise would cause if the stimuli were to occur in your own sitting-room.

Try to make the ratio between the numbers you assign correspond to the ratio between the annoyance caused by each stimulus. For example, if you consider a stimulus would be twice as annoying as a stimulus which has been assigned the value of 100, you should assign it the value of 200. Alternatively, if you consider it to be only half as annoying you should assign it the value of 50.

Remember to base your judgement on the noise alone and not on the vibration.

After receiving the first stimulus, assigned the value of 100, you will be presented with four practice stimuli. You will then be given an opportunity to ask questions before starting the experiment. This will also begin with the stimulus assigned the value of 100.

Please sit in the same comfortable upright posture throughout the experiment and keep your feet and legs as still as possible.

APPENDIX 5.6

INSTRUCTIONS TO SUBJECTS FOR SESSION C, EXPERIMENT 4

You will be presented with many different types of vibration and noise which might occur in the house. Your task will be to assign numbers to each stimulus.

The first stimulus you will receive will be assigned the value of 100. After each of the following stimuli please assign a number to indicate the annoyance that the combination of noise and vibration would cause if the stimuli were to occur in your own sitting-room.

Try to make the ratio between the numbers you assign correspond to the ratio between the annoyance caused by each stimulus. For example, if you consider a stimulus would be twice as annoying as a stimulus which has been assigned the value of 100, you should assign it the value of 200. Alternatively, if you consider it to be only half as annoying you should assign it the value of 50.

Remember to base your judgement on the combination of noise and vibration, not on the noise alone or the vibration alone.

After receiving the first stimulus, assigned the value of 100, you will be presented with four practice stimuli. You will then be given an opportunity to ask questions before starting the experiment. This will also begin with the stimulus assigned the value of 100.

Please sit in the same comfortable upright posture throughout the experiment and keep your feet and legs as still as possible.

APPENDIX 5.7

MEDIAN MAGNITUDE ESTIMATES FROM EXPERIMENT 4

Session A: Subjects Assessed the Vibration

L_{AE} (dB(A))

VDV ($ms^{-1.75}$)		N_0 –	N_1 54	N_2 59	N_3 64	N_4 69	N_5 74	N_6 79
	V_1 0.07	22	25	25	27	25	25	10
	V_2 0.10	50	75	75	67	73	55	27
	V_3 0.14	100	78	100	100	100	100	85
	V_4 0.20	100	113	110	128	150	145	150
	V_5 0.28	162	150	175	167	167	200	190
	V_6 0.40	200	212	200	210	250	250	250

Session B: Subjects Assessed the Noise

L_{AE} (dB(A))

VDV ($ms^{-1.75}$)		N_1 54	N_2 59	N_3 64	N_4 69	N_5 74	N_6 79
	V_0 0.00	25	67	100	150	200	300
	V_1 0.07	30	73	100	150	200	250
	V_2 0.10	27	73	100	150	250	300
	V_3 0.14	45	75	100	150	200	255
	V_4 0.20	25	70	100	150	200	300
	V_5 0.28	25	75	100	150	200	274
	V_6 0.40	25	61	100	150	250	300

Session C: Subjects Assessed the Noise and Vibration

L_{AE} (dB(A))

VDV ($ms^{-1.75}$)		N_0 -	N_1 54	N_2 59	N_3 64	N_4 69	N_5 74	N_6 79
	V_0 0.00	-	25	50	80	98	195	200
	V_1 0.07	20	45	65	90	120	178	250
	V_2 0.10	25	50	73	100	125	184	210
	V_3 0.14	30	50	100	100	150	180	250
	V_4 0.20	52	85	78	113	140	210	215
	V_5 0.28	100	100	128	150	165	200	300
	V_6 0.40	105	125	155	180	250	250	287

APPENDIX 6.1

INSTRUCTIONS FOR PRACTICE SESSION OF EXPERIMENT 5

This experiment requires you to assign numbers corresponding to the annoyance caused by different vibration stimuli.

In order to give you some practice using this technique, you will first assign numbers to lines according to their length. The first line shown to you will be assigned a value of 100. Your task will be to assess the length of other lines with reference to the first.

For example, if the second line you are presented with appears to be 4 times the length of the first, it should be assigned a value of 400. Alternatively, if it appears to be only ¼ of the length of the first, it should be assigned the value of 25.

APPENDIX 6.2

INSTRUCTIONS TO SUBJECTS FOR EXPERIMENT 5

You will be presented with many different types of vibration which might occur in a house. Your task is to assign numbers to the vibration stimuli by comparing them with the noise stimulus.

The noise stimulus is given the value of 100 and will be repeated before every four vibration stimuli. After each vibration stimulus, please assign a number to indicate the annoyance that it would cause if it were to occur in your own home.

Try to make the ratio between the numbers you assign to each vibration stimulus and the value of the noise stimulus (i.e. 100) correspond to the ratio between the annoyance caused by the noise and the vibration. For example, if you consider that a vibration stimulus is twice as annoying as the noise stimulus, you should assign it the value of 200. Alternatively, if you consider it to be only half as annoying as the noise, you should assign it the value of 50.

After receiving the first noise stimulus, you will be presented with four practice vibration stimuli. You will then be given an opportunity to ask questions before starting the experiment.

Please sit in the same comfortable upright posture throughout the experiment and keep your feet and legs as still as possible.

You may stop the experiment at any time by pressing the red STOP button.

APPENDIX 7.1

INSTRUCTIONS FOR PRACTICE SESSION OF EXPERIMENT 6

This experiment requires you to assign numbers corresponding to the annoyance caused by different vibration stimuli.

In order to give you some practice using this technique, you will first assign numbers to lines according to their length. The first line shown to you will be assigned a value of 100. Your task will be to assess the length of other lines with reference to the first.

For example, if the second line you are presented with appears to be 4 times the length of the first, it should be assigned a value of 400. Alternatively, if it appears to be only ¼ of the length of the first, it should be assigned the value of 25.

APPENDIX 7.2

INSTRUCTIONS TO SUBJECTS FOR EXPERIMENT 6

You will be presented with many different types of vibration and noise which might occur in a house. Your task will be to assign numbers to each stimulus.

The first stimulus you will receive will be the reference stimulus and will be assigned the value of 100. The reference stimulus will be repeated before every four test stimuli. After each test stimulus please assign a number to indicate the annoyance that the combination of noise and vibration would cause if they were to occur together in your own sitting-room.

Try to make the ratio between the numbers you assign correspond to the ratio between the annoyance caused by the reference and the test stimuli. For example, if you consider that a test stimulus is twice as annoying as the reference stimulus, you should assign it the value of 200. Alternatively, if you consider it to be only half as annoying as the reference stimulus you should assign it the value of 50.

Remember to base your judgement on the combination of noise and vibration, not on the noise alone or the vibration alone.

After receiving the first reference stimulus, assigned the value of 100, you will be presented with four practice stimuli. You will then be given an opportunity to ask questions before starting the experiment. This will also begin with the reference stimulus.

Please sit in the same comfortable upright posture throughout the experiment and keep your feet and legs as still as possible.